NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

MANNING AND MAINTAINABILITY OF A SUBMARINE UNMANNED UNDERSEA VEHICLE (UUV) PROGRAM: A SYSTEMS ENGINEERING CASE STUDY

by

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September 2010

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REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.			
1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** September 2010	**3. REPORT TYPE AND DATES COVERED** Master's Thesis	
4. TITLE AND SUBTITLE Manning and Maintainability of a Submarine Unmanned Undersea Vehicle (UUV) Program: A Systems Engineering Case Study			**5. FUNDING NUMBERS**
6. AUTHOR(S) Troy D. Vandenberg			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

The purpose of this thesis is to study the manning and maintainability requirements of a submarine unmanned undersea vehicle (UUV) program. This case study reviews current commercial and military applications of UUVs and applies their principles to the missions of the Navy's submarine force. Past and current UUV efforts are lacking requirements documents and the formal systems engineering process necessary to produce a successful program of record. Therefore, they are not being funded for use by the war-fighter. The Navy must develop formal concepts of operations (CONOPS) for the missions and systems that it wants to produce and allow industry to begin development for a formal future UUV program. Furthermore, the military has developed countless unmanned systems that have been developed for use in the water, on the ground and in the air, from which the Navy can apply important lessons learned. Lastly, analysis suggests that the Navy should continue to support the use of a submarine detachment for operation and maintainability of future vehicle programs.

14. SUBJECT TERMS Unmanned Undersea Vehicles, UUV, Manning, Maintainability, Submarine Missions, Systems Engineering			**15. NUMBER OF PAGES** 137
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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MANNING AND MAINTAINABILITY OF A SUBMARINE UNMANNED UNDERSEA VEHICLE (UUV) PROGRAM: A SYSTEMS ENGINEERING CASE STUDY

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

The purpose of this thesis is to study the manning and maintainability requirements of a submarine unmanned undersea vehicle (UUV) program. This case study reviews current commercial and military applications of UUVs and applies their principles to the missions of the Navy's submarine force. Past and current UUV efforts are lacking requirements documents and the formal systems engineering process necessary to produce a successful program of record. Therefore, they are not being funded for use by the war-fighter. The Navy must develop formal concepts of operations (CONOPS) for the missions and systems that it wants to produce and allow industry to begin development for a formal future UUV program. Furthermore, the military has developed countless unmanned systems that have been developed for use in the water, on the ground and in the air, from which the Navy can apply important lessons learned. Lastly, analysis suggests that the Navy should continue to support the use of a submarine detachment for operation and maintainability of future vehicle programs.

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EXECUTIVE SUMMARY

A. BACKGROUND

In 2004, the Navy unveiled the Sea Power 21-inspired Unmanned Undersea Vehicle (UUV) Master Plan, which defined the nine missions of UUVs and the four different vehicle classes that could support those missions. The Navy has made some fundamental changes in their development, testing, and acquisition of UUVs, but even with the Master Plan's recommendations, years later, there is no current submarine UUV program of record. This thesis utilized government and industry resources to focus on the systems engineering fundamentals that are necessary to have a successful submarine UUV program in the near future. Moreover, the intent of this thesis was to research past and current programs and missions and provide recommendations for the manning and maintainability aspects of the systems engineering lifecycle. To do this, the research started with the large-scale concept of UUVs and eventually focused on the manning and maintainability aspects that are specifically related to UUVs in support of submarine missions.

The purpose of this thesis was to provide recommendations for the steps necessary to have a successful submarine UUV program of record. Additionally, the thesis discusses the impact that unmanned undersea vehicles will have on the submarine force, focusing on the two key areas of manning and maintainability. In doing this research, assumptions have been made that the technological challenges of deploying UUVs from, or in tandem with, submarines are ones that will be possible to overcome. Lastly, this thesis was completed as an UNCLASSIFIED document. Though some of the research did involve classified discussions, presentations, and documents, they were not used in any capacity for the final write-up. As a result, some systems, technologies, missions, and information have been presented in a focus different or separated from doctrine discussed directly by the United States Navy.

B. UTILIZING UUVS TO SUPPORT SUBMARINE MISSIONS

UUVs are not a new concept. The necessary technologies exist and members of industry and military have been using forms of UUVs for many years. This does not mean, however, that UUVs are ready to perform all missions required of their military stakeholders. UUV missions lack importance unless there is a clear benefit to be gained from their deployment. Three high level advantages of unmanned systems in the maritime domain are that they can decrease cost, increase capability, and reduce risk.

The two major factors that contribute to the various types of UUVs are size and complexity. UUVs are broken into four classes, based on their displacements. For the intent of a submarine program, the two larger classes (as defined by the 2004 UUV Master Plan) of Heavy Weight Vehicle (HWV) (21-inch diameter and less than 3000 pounds of displacement) and Large Vehicle (greater than 26-inch diameter and approximately 20,000 pounds of displacement) are considered. Additionally, unmanned system complexity is a factor of the level of autonomy, which can range between human-operated and fully autonomous. Ideally, a UUV program would utilize a fully autonomous vehicle, but this is one of the technical challenges currently faced by the Navy and the industrial developers. Though the technology does exist, it requires the confidence of the operator moving forward.

Future naval battles will rely heavily on advantages gained through the combination of strategies, tactics, procedures, and technologies called network-centric warfare and implemented through the strategy of ForceNet. These ideas rely heavily on Joint Force assets working together with common communication nodes. Large-scale undersea networks, like those adhering to ForceNet will be used heavily in the future of undersea warfare (USW), with UUVs acting as crucial communication nodes to and from submarine and surface assets. Out of the nine key mission areas discussed in the 2004 UUV Master Plan, three specific missions should be considered for a near-term submarine UUV program and can be evaluated as part of the overall ForceNet image. These missions are:

- **Intelligence, Surveillance, and Reconnaissance (ISR).** There are four fundamental tasks necessary to complete an ISR mission: collect, communicate, process, and act. Due to the simplistic nature and emerging technologies, the submarine ISR mission-set will see the first full scale use of UUVs.
- **Communications.** Communication is an important aspect for all military operations. Underwater communications are complex and pose many problems in the area of USW. One technology is to utilize digital acoustic communications in modem-like bursts to communicate between a submarine and a network of UUVs acting as communication nodes. There are multiple programs being worked on by industry that make use of this theory and have the ability to perform the desired missions.
- **Anti-Submarine Warfare (ASW).** Submarines have always played a vital role in ASW. The force multiplication factor added by UUVs will allows them to constantly patrol and monitor areas of interest. UUVs and friendly submarines could remain in constant communication, relaying valuable mission and classification data, which would drastically increase the overall effectiveness of current ASW tactics.

Though there have been past programs, and current projects, that focus on the levels of complexity, two vehicle sizes, and three missions discussed, there is no current UUV program of record relating to submarine operations. The extinct programs and current projects lend themselves to lessons learned for future success. The submarine UUV programs that have failed can be attributed to lack of requirements and improper system development. Each of these programs, however, has given the Navy valuable insight on the manning and maintainability requirements of future UUV programs.

The biggest technical challenges faced by past programs have been the interaction between the submarine and UUV. Possible submarine-UUV interactions include:

- **Launch and Recovery.** The ability to launch and recover a UUV from a submarine is the greatest technical challenge that has led to the failure of

at least two programs [Long-term mine reconnaissance system (LMRS) and mission reconfigurable UUV (MRUUV)]. Emerging technologies are coming close to making this mission possible, but both physical space and maintenance routines are still a challenge on board a submarine.

- **Launch without Recovery.** Setting up a scenario with UUV system launch via a torpedo tube, missile tube, or dry-deck shelter will allow for covert deployment of one or more UUVs while avoiding the drawbacks associated with space considerations to support organizational level maintenance and technical risks of torpedo tube recovery. Upon mission completion, the UUV could either be abandoned or recovered by use of a support ship.

- **Non-physical Interactions.** Regardless of the form of deployment, there are several possible non-physical interactions between the submarine and UUV, including: mission control, consumer/interrogator of data, and docking station delivery. Each of these interactions hold true for all forms of UUV launch and recovery. Designing UUV and submarine interactions independent of the launch source will help transition to a less "platform centric" design of UUV systems. When systems can be designed without the platform in mind, there is more room for growth and an increased chance of long-term success for a program.

Additionally, Unmanned Ground Vehicles (UGVs) and Unmanned Aerial Vehicles (UAVs) have been in use longer than UUVs. This longevity provides the UGVs and UAVs with valuable lessons learned that can be applied to their undersea counterparts. This thesis discusses eleven lessons learned that can apply to the manning and maintainability practices. These lessons are:

- Uncertainty promotes survival
- Simpler solutions provide better foundations
- Many simple cooperating agents are superior to one complex agent

- Maintenance should be done at the user level
- System requirements should be clear up front
- Acquire reliability data throughout all stages of development
- Structure a process for sharing data
- Limit the number of design configurations
- Consider supportability up front
- Endurance has its benefits
- Minimize the levels of redundancy

C. SYSTEMS ENGINEERING OF A SUBMARINE UUV PROGRAM

There are four fundamental stages to system design lifecycle. This four-stage process has analysis, verification, and feedback occurring simultaneously with each step. All four stages are required for a program to be "Systems Engineered" correctly. To successfully complete a mission or set of missions, the four stages of the process need to occur in the following order:

- Develop Requirements, based on missions
- Determine Tasks, based on requirements
- Create Functions, based on tasks
- Design Components, based on functions

Proper requirement definitions are produced with the system stakeholders and are derived from the mission requirements. Unfortunately, this stage is often not understood by the customer and requires the attention of a formally trained Systems Engineer. Many engineers feel the role of the systems engineering process begins at the requirements document, when in fact the Systems Engineer should work directly with the stakeholder to understand the requirements and eventually formalize those requirements. Current Navy submarine UUV projects have shown success in various at sea tests, but are not part

of a formal program and have included unclear, if not completely undefined, requirements. This shortfall has meant that even though the programs may have performed up to the operator's expectations, the funding line is not in place for future development of the systems and, as a result, may leave them forever sidelined.

Feedback should not only be done internal to the system, but must be used from similar programs to gather valuable data necessary to maximize the probability of successfully engineering a new complex system. Lack of feedback has caused past UUV programs, with clearly stated requirements, to develop to a certain level and then become cancelled by the Navy, for there to be a new programs started from the beginning. Ideally, it is not only important that a program has requirements, but it will also need to take lessons learned from previous similar programs.

In the systems lifecycle, there are three different stages of design: conceptual, preliminary, and detail. This incremental process allows the inter-stage feedback to provide real time response and allows for flexibility in the growth of the design process. Future submarine UUV systems should account for manning and maintainability during the developmental stages of the systems engineering lifecycle.

Sample concepts of operations (CONOPS) were created to offer suggestions for the specific types of missions the Navy should pursue for a submarine UUV program and the manning and maintainability suggestions that would apply to these missions. The two discussed CONOPS were:

- **Group of Submarine Launched UUVs.** Small, torpedo tube-launched UUVs would be ideal to complete an ISR mission. Several of these UUVs would be launched from a submerged submarine and would transition into an area of interest. The lead UUV would surface and extend a mast to collect intelligence data. The other UUVs would act as communication nodes and relay the information to be analyzed onboard back to the submarine. This mission would require a cadre of five individuals aboard the submarine operating the systems and performing minimal organizational level maintenance during the deployment.

- **Group of Large Diameter UUVs (LDUUVs).** LDUUVs could be launched from a Littoral Combat Ship (LCS) to complete a harbor monitoring and tracking ASW mission. Multiple LDUUVs would be launched and recovered from the LCS, while the submarine would remain near the operational area and communicate with the LDUUVs, relaying critical mission data. This scenario would require a small group of operators on the submarine and a mix of ten Navy personnel and contractors on board the LCS. This scenario supports longer missions and would require that extensive maintenance be performed on board the LCS.

These CONOPS do not provide all of the solutions of decision makers, but rather gives them a stepping point for future submarine UUV program development.

D. CONCLUSIONS AND RECOMMENDATIONS

The government is devoting much effort in the formal training and proper use of Systems Engineers. As a result, many programs are seeing an increase in their productivity during the early stages of lifecycle development. Unfortunately, many programs are being researched and tested using informal processes through government organizations like ONR and DARPA and are ultimately cancelled due to funding concerns. Though there is a place for research and development of technologies, the current procedures are sidelining UUV programs that have performed up to, and in some cases beyond, operator's expectations. Many programs in development are outside the needs of preliminary development and must be pursued in the form of a formal program. To ensure a successful program, the systems will need to be developed using a formal systems engineering process. Adhering to these processes will ensure that a successful program will retain funding.

To do this, the Navy must start with a clearly defined mission and then follow four basic systems engineering steps to develop the ideas into systems. This will require the government to produce ideas independent of the end product in mind. The intent of the thesis was to analyze the impact of a submarine UUV program on the manning and

maintenance of the submarine force. Outside of the systems engineering and development process concerns discussed previously, this thesis comes to three conclusions:

- **Focus the Missions.** This study shows that the Navy should only focus on three short-term missions for a submarine UUV program: ISR, communications, and ASW. These missions were chosen based on operator demands, and are the missions that are most easily accomplished with the current technologies available. The challenges (other than budgetary ones) that face current ISR and ASW missions are longevity, and launch and recovery. This research suggested ways of creating programs that will gain successful mission results in the near-term, while still adhering to the technical constraints faced by UUV developers. One example includes the use of multiple vehicles to complete the same mission as a single long endurance vehicle.

- **Learn Lessons from UGVs and UAVs.** UGVs and UAVs provide several similarities to UUVs and were the basis for the eleven lessons learned pertaining to the development of UUV systems. The eleven lessons were diverse in their relation to UUVs, but all provided ideas that should be considered during the front-end system development process that directly relate to the manning and maintainability of a program of record. These lessons (along with any others shared amongst the program offices) should all be considered prior to spending more money on testing, developing, and fielding new unmanned systems.

- **Consider Manning and Maintainability.** The original intent of the research was to understand the manning and maintenance models and concerns that UUVs would have on the submarine force. Past systems have neglected the impact of logistics on the deployment of new systems, and it is important that the developers of a submarine UUV program do not forget this. The limited size, space, and crew aboard a SSN will

require these thoughts to be fully considered before the program enters the advanced development stages. Analysis suggests that operators should continue to be part of a cadre of submarine qualified sailors with diverse ratings. These operators must be qualified to both operate and maintain the systems at both the organizational and intermediate maintenance levels.

The intent of this thesis was to focus on the abstract, high-level concepts that will effect the manning and maintainability aspects of the systems engineering process. As a result, the scope of this thesis has led to several areas of further research for future studies. The future work to expand this thesis into real world applications should be done in the areas of trade studies, technologies, lessons learned, and requirements.

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LIST OF ACRONYMS AND ABBREVIATIONS

A_o	Operational Availability
ACOMMS	Acoustic Communications
ADO	Advanced Development Office
ALV	Autonomous Land Vehicle
ANSE	American Society of Naval Engineers
AUV	Autonomous Underwater Vehicle
BPAUV	Battlespace Preparation Autonomous Underwater Vehicle
C2S	Command-and-Control System
CBA	Cost Benefit Analysis
CG	Guided Missile Cruiser
CI	Configuration Item
CN3	Communications / Navigation Network Node
CONOPS	Concept of Operations
COTS	Commercial Off-the-Shelf
CSG	Carrier Strike Group
DARPA	Defense Advanced Research Projects Agency
DAU	Defense Acquisition University
DDG	Guided Missile Destroyer
DDS	Dry Deck Shelter
DEVRON	Development Squadron
DoD	Department of Defense
DSSN	Distributed Surveillance Sensor Network
EFFBD	Enhanced Functional Flow Block Diagram
EOD	Explosive Ordnance Disposal
ESG	Expeditionary Strike Group
ET	Electronics Technicians
FFBD	Functional Flow Block Diagram
FFG	Guided Missile Frigate
FT	Fire Control Technician
FY	Fiscal Year
HLD	Homeland Defense
HWV	Heavy Weight Vehicle
ID	Identification
IDEF0	Integration Definition for Function Modeling
IO	Information Operations
ISR	Intelligence, Surveillance, and Reconnaissance
JIATF	Joint Interagency Task Force
LCC	Lifecycle Cost
LCS	Littoral Combat Ship
LDO	Limited Duty Officer
LDUUV	Large Diameter Unmanned Undersea Vehicle
LMRS	Long-term Mine Reconnaissance System

LRU	Line Replaceable Unit
LWV	Light Weight Vehicle
MBSE	Model-Based Systems Engineering
MCM	Mine Counter Measures
MM	Machinist’s Mate
MMS	Mission Management System
MTBF	Mean Time Between Failure
MTBM	Mean Time Between Maintenance
NDIA	National Defense Industrial Association
NEC	Navy Enlisted Classification
NMRS	Near-term Mine Reconnaissance System
O&S	Operations and Support
OEF	Operation Enduring Freedom
OIF	Operation Iraqi Freedom
ONR	Office of Naval Research
ORD	Operational Requirements Document
PEO LMW	Program Executive Office Littoral and Mine Warfare
PLM	Product Lifecycle Management
PSU ARL	Pennsylvania State University Applied Research Laboratory
REMUS	Remote Environmental Monitoring Units
ROV	Remotely Operated Vehicle
RSTA	Reconnaissance, Surveillance, and Target Acquisition
SCM	Search, Classify, Map
SOF	Special Operations Forces
SPAWAR	Space and Naval Warfare Systems Command
SSN	Nuclear-powered Submarine
SSBN	Nuclear-powered Ballistic Missile Submarine
SSGN	Nuclear-powered Guided Missile Submarine
STS	Sonar Technician Subsurface
TCS	Time Critical Strike
TUNAS	Tracking of Underwater Narco-subs using Autonomous Submersibles
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
UMS	Unmanned Maritime System
UNTL	Universal Naval Task List
USAF	United States Air Force
USN	United States Navy
USW	Undersea Warfare
UUV	Unmanned Undersea Vehicle
VMS	Vehicle Management System
VSW	Very Shallow Water
WHOI	Woods Hole Oceanographic Institute

ACKNOWLEDGEMENTS

There are many people who have helped me in finishing this thesis and completing my degree at the Naval Postgraduate School.

First, I would like to show gratitude to my advisors Professor Cliff Whitcomb and RADM "Jerry" Ellis, USN (ret) who combined to help me pick a topic in my interests in systems engineering. I am grateful for the questions they asked, contacts they provided, and advice they gave during the entire process.

Second, I express thanks the members of both military and commercial entities that have opened their doors to share their ideas, answer my questions, and give valuable feedback during the writing process. Moreover, I acknowledge the leaders and members of the American Society of Naval Engineers and National Defense Industrial Association for offering great conferences and the means for social and professional mentoring. An additional thank you goes out to Northrop Grumman who provided research funding to make this and other student's theses possible.

Third, I appreciate the fellow students who were invaluable as peers, friends, and mentors. Much of my academic success can be attributed to MAJ Joseph Brocht, USA; CPT Thomas McMurtrie, USA; and LT Christopher Schindler, USN who combined to make the experience both educational and entertaining.

Last, and certainly not least, I would like to give thanks to my wife Jessica and son Brayden. It was their understanding and support that made is possible for me to travel and spend long hours researching, writing, and editing.

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I. INTRODUCTION

A. BACKGROUND

In 2004, the Navy unveiled the Sea Power 21-inspired Unmanned Undersea Vehicle (UUV) Master Plan, which defined nine missions of UUVs and four different vehicle classes that could support those missions. On top of the generic missions and vehicles, the new Master Plan defined six key recommendations for moving forward (Department of the Navy, 2004):

1. Develop four UUV classes: Man Portable (<100 pounds), Light Weight (~500 pounds), Heavy Weight (~3000 pounds), and Large (~20,000 pounds)
2. Develop standards and implement modularity
3. Establish a balanced UUV technology program
4. Increase experimentation in UUV technology
5. Coordinate with other unmanned vehicle programs
6. Field systems in the fleet

The Navy has made some fundamental changes in their development, testing, and acquisition of UUVs, but even with these recommendations, years later, there is no current submarine UUV program of record. This thesis utilized government and industry resources to focus on the systems engineering fundamentals that are necessary to have a successful submarine UUV program in the near future. Moreover, the intent of this thesis was to research past and current programs and missions and provide recommendations for the manning and maintainability aspects of the systems engineering lifecycle. To do this, the research started with the large-scale concept of UUVs and eventually focused on the manning and maintainability aspects that are specifically related to UUVs in support of submarine missions.

The analysis began with generic UUV missions and systems used by both industry and military entities. After the discussion of generic use of UUVs, the next

focus is on submarine missions that can be supported by UUVs, and which of past and present Navy programs can support those missions. Next, eleven lessons learned from unmanned ground vehicles (UGVs) and unmanned aerial vehicles (UAVs) are introduced and discussed.

The main focus of the thesis was a systems engineering discussion with extra emphasis put into the manning and maintainability stages of the systems engineering lifecycle, and the impacts these stages will have on the submarine fleet after UUV implementation. This discussion leads into the introduction of two sample concepts of operations (CONOPS) that integrate all aspects of research of the thesis. The purposes of the CONOPS are to lay out recommendations for the Navy as they move forward in development of a formal UUV program.

B. PURPOSE

The purpose of this thesis was to provide recommendations for the steps necessary to have a successful submarine UUV program of record. Additionally, the thesis discusses the impact that unmanned undersea vehicles will have on the submarine force, focusing on the two key areas of manning and maintainability. In doing this research, assumptions have been made that the technological challenges of deploying UUVs from, or in tandem with, submarines are challenges that the Navy can overcome.

C. RESEARCH QUESTIONS

This thesis addresses the following research questions as a means of research and direction for the thesis.

1. Which UUV missions are most likely to occur in the near future? Are these missions feasible for the Navy?
2. Which of the UUV missions are most applicable to support the submarine force? Will these missions require deployment/retrieval from a submarine platform?

3. Have unmanned ground vehicles (UGVs) and unmanned aerial vehicles (UAVs) provided any lessons learned during their employment in military operations?

4. Will UUVs have a detachment to support their use, or will they utilize ship's force? Will the operators be contractors or military? If military, which ratings will be used to operate these systems? Will additional ratings be necessary to accommodate the mission sets? What training is necessary for the operators?

5. What changes in the current infrastructure for maintenance and system support are necessary to complete the missions of both the UUVs and submarines? Can the maintenance be done on board (operator level), or will other vessels and facilities be required? Does the use of UUVs change the original schedule of the host submarine?

D. BENEFIT OF STUDY

This thesis begins the valuable systems engineering necessary to develop and deploy UUVs for use by the submarine force. Additionally, the collaborative nature of this thesis aids in breaking down the "stove-pipe" system currently in place for UUV development.

E. SCOPE AND METHODOLOGY

It is important to note that this thesis is UNCLASSIFIED. Though some of the research did involve classified discussions, presentations, and documents, they were not used in any capacity for the final write-up. As a result, some systems, technologies, missions, and information have been presented in a focus different or separate from doctrine discussed directly by the United States Navy (USN). These differences are understood, but bear little relevance to the overall conclusions and recommendations cited by this work.

This scope of research was limited to only unmanned undersea vehicles and their impact on the submarine fleet. Though it takes lessons learned from UAVs and UGVs, it

will neglect the impact of these systems and the collaborative effort they can bring to the Navy. Similarly, other vessels and missions may take advantage of UUVs in the Navy but the research focused specifically on UUVs designed to aid with submarine missions. The only non-submarine platforms that were researched were vessels that may be necessary for system support or deployment [i.e., Littoral Combat Ship (LCS) or submarine tenders].

The research began by attending conferences relevant to UUVs. These conferences, hosted by the National Defense Industrial Association (NDIA) and the American Society of Naval Engineers (ASNE) had the dual benefit of providing useful information about UUV systems and created networking amongst the author and Department of Defense (DoD) and industry contacts. After generating a list of useful contacts after each conference, the author framed questions specific to their expertise and conducted interviews via email, phone, and in person.

This information helped focus efforts toward the manning and maintainability aspects of UUV operations and generated the needs and constraints faced by the stakeholders of the future UUV systems. The interviews were followed by researching current UUV systems (which lead to more interviews) and exploring previous impacts of both UGVs and UAVs on their operators and maintainers. This data was analyzed and coupled together to reach the conclusions and recommendations of this thesis and to provide areas for additional investigations.

F. CHAPTER SUMMARY

This chapter outlined the background, purpose, research questions, benefit of study, and scope and methodology that has gone into the development of the thesis. The content of this section provided the focus areas necessary to direct the thesis research.

II. UUV MISSIONS AND SYSTEMS

A. INTRODUCTION

UUVs are not a new concept. The necessary technologies exist and members of industry and military have been using forms of UUVs for many years. For example, a torpedo is a type of UUV. This does not mean, however, that UUVs are ready to perform all missions required by their military stakeholders. This chapter will outline various UUV missions for the Navy and introduces various industry vehicles that support similar operations. It is not the intent of this chapter to directly link military missions to specific brands of UUVs.

B. UUV MISSIONS

1. Advantages of UUVs for Military Operations

UUV missions lack importance unless there is a clear benefit to be gained from their deployment. To address this, dozens of unique advantages of UUVs could be listed; instead, the list was refined to three distinct advantages of using unmanned systems in the maritime domain. The three high level advantages of unmanned systems are decreased cost, increased capability, and reduced risk.

a. Decreased Cost

Properly distributing UUVs will greatly reduce the cost of patrolling the vast oceans (Heatley, Horner, & Kragelund, 2005). Though the individual systems may cost between several hundred thousand and a few million dollars, they are much cheaper than the SSN equivalent of over two billion dollars. Additionally, as will be discussed in the systems engineering chapter, the manning and maintainability requirements for individual UUVs have the ability drastically reduce the lifecycle costs (LCC) of unmanned versus manned systems. This thesis does not evaluate a full cost benefit analysis (CBA) of UUVs; even without this analysis it immediately is evident the cost savings these systems provide to the military.

b. Increased Capability

Though cost is an initial driver for implementing unmanned systems, this cost reduction will not happen overnight. Initial UUV deployments will actually result in an increase in cost (and manning), since the Navy will continue to deploy manned systems in conjunction with the new unmanned systems. What the Navy will gain, however, is an increased capability of the systems that take advantage of UUVs. Upon achieving "steady state," it is projected that UUVs will increase capability <u>and</u> reduce manning <u>and</u> decrease cost.

The missions provided by UUVs are not new to the Navy, but the situations in which these missions can be accomplished are the capabilities the UUVs provide. Amongst the capabilities is the access to unique environments provided by their smaller, less detectable size, in comparison to manned systems. This versatility provides an increased benefit in several mission sets in the littoral waterways, including mine detection, payload delivery, and intelligence gathering. Another capability, often utilized in UAVs, is collaborative networking. A group of UUVs can fuse sensor data and provide communication nodes back to the manned host platform, increasing the effectiveness of specific undersea mission areas (Fraser, 2009).

c. Reduced Risk

Unmanned systems remove the operators from the hazardous environments in which they operate, instantly creating a safer environment for the war-fighters. Eliminating the manned portion of these missions will additionally reduce risk by allowing the operator to focus on mission planning, situation and knowledge management, and decision making (Fraser, 2009).

2. UUV Sub-Pillar Missions

The 2004 UUV Master Plan outlines nine essential missions that can be linked to UUVs, called "sub-pillars." These sub-pillars, in "priority" order, are (Department of the Navy, 2004):

1. Intelligence, Surveillance, and Reconnaissance (ISR)
2. Mine Countermeasures (MCM)
3. Anti-Submarine Warfare (ASW)
4. Inspection / Identification (ID)
5. Oceanography
6. Communication / Navigation Network Nodes (CN3)
7. Payload Delivery
8. Information Operations (IO)
9. Time Critical Strike (TCS)

a. Vision of Sea Power 21

In a 2002 article in *Proceedings Magazine*, the then Chief of Naval Operations Admiral Vern Clark outlined his vision for how the future Navy will organize, integrate, and transform itself to the 21st century. He called his new vision "Sea Power 21." Sea Power 21 consists of three fundamental concepts of naval operational effectiveness: Sea Strike, Sea Shield, and Sea Basing. Each of these capabilities was constructed around the main concept of ForceNet which is the "operational construct and architectural framework … integrating warriors, sensors, command and control, platforms, and weapons" into a state-of-the-art combat force (Clark, 2002).

Figure 1. Initial vision of Sea Power 21 (From: Clark, 2002)

b. Relating Sea Power 21 to Nine Sub-Pillars

UUVs provide a key component to the vision of Sea Power 21, utilizing the UUV advantages of reducing risk and increasing capabilities through force multiplication. The nine sub-pillars can be grouped into categories relating directly to the four segments of Sea Power 21, shown in Table 1. The missions that specifically relate to submarine related missions will be further detailed in the next chapter.

Table 1. Mapping of the nine sub-pillars to Sea Power 21 vision (After: Department of the Navy, 2004)

ForceNet	**Sea Strike**	**Sea Shield**	**Sea Basing**
– ISR – Oceanography – CN3	– IO – TCS	– ASW – MCM – Inspection/ID	– Payload Delivery

C. UUV SYSTEMS

The number of missions that can be supported by UUVs is endless. This section will discuss the four vehicle classes defined by the 2004 Navy UUV Master Plan and list some of the many vehicles that have been developed for commercial and military use.

1. UUV Vehicle Classes

There are four vehicle classes for UUVs as defined by the 2004 Navy UUV Master Plan. These classes are 1) Man-Portable, 2) Light Weight Vehicle (LWV), 3) Heavy Weight Vehicle (HWV), and 4) Large Vehicle, as characterized in Table 2.

Table 2. Definition of UUV classes for nominal levels of performance (After: Department of the Navy, 2004)

Class	**Diameter (inches)**	**Displacement (pounds)**	**High Load Endurance (hours)**	**Low Load Endurance (hours)**	**Payload (cubic feet)**
Man-Portable	3 – 9	< 100	< 10	10 – 20	< 0.25
LWV	12.75	~ 500	10 – 20	20 – 40	1 – 3
HWV	21	< 3000	20 – 50	40 – 80	4 – 6
Large	> 36	~ 20,000	100 – 300	>> 400	15 – 30

The vehicle class diversity allows for flexibility in vehicles for meeting the nine UUV sub-pillar capabilities outlined in the 2004 Master Plan. Each class and sub-pillar has several different specific missions that can be accomplished, and Table 3 links some of the generic missions of each sub-pillar to its applicable vehicle class.

Table 3. Classes of UUVs mapped to generic missions of the nine sub-pillars (After: Department of the Navy, 2004)

Mission	**Man-Portable**	**LMV**	**HWV**	**Large**
ISR	Special Purpose	Harbor	Tactical	Persistent
MCM	VSW / SCM Neutralizers	Operating Area Clearance	Clandestine Recon	
ASW				Hold at Risk
Inspection/ID	HLD / Force Protection			
Oceanography		Special Purpose	Littoral Access	Long Range
CN3	VSW / SOF	Mobile CN3		
Payload Delivery				SOF, ASW, MCM, TCS
IO		Network Attack	Submarine Decoy	
TCS				SOF, ASW, MCM, TCS

2. Sample UUV Platforms

It is important from an economic standpoint to combine, wherever possible, commercial and military development of UUVs. This concept was researched by an NDIA Undersea Warfare (USW) division working group for PMS 403 in a 2004 study entitled "Open Architecture, Dual Commercial/Military Use of Large Displacement Unmanned Undersea Vehicles." This study drew a main conclusion of the limitations of 21-inch HWVs from an energy storage and payload perspective. The study suggested that large UUVs increase the operational capabilities needed by the future Navy, and focused on various ways of deploying such systems from host platforms (to be discussed in further detail in the next chapter). In order to be able to afford these large UUVs, the Navy cannot be the only stakeholder. Though, at the time of the study, there was no clear demand for large UUVs in the private sector, NDIA researchers suggested that Government partnerships and incentives may create a future demand (National Defense Industrial Association, 2004).

This study confirms the desire of the Navy to use commercial off-the-shelf (COTS) systems for future UUV needs. The use of COTS systems will require today's UUVs to be upgraded to military standards prior to Navy use. Though this may not be an

easy task, current industry vehicles used by private firms and/or developed by research institutes can provide a baseline for the technology and capabilities that will be seen in the Navy's future UUVs. Some of the many potential COTS vehicles are introduced in the following pages and related to the UUVs discussed in later parts of this thesis. The vehicles featured in Table 4 were selected due to the diverse nature with respect to each other.

Table 4. Summary of sample UUVs analyzed

Name	**Length**	**Diameter**	**Max Depth**	**Endurance**
REMUS-100	63 inches	7.5 inches	400 feet	8 hours @ 5 knots
Bluefin-21	130 inches	21 inches	600 feet	18 hours @ 3 knots
ASM-X	20 feet	21 inches	Unknown	30 hours @ 2 knots
HUGIN 3000	17 feet	3.3 feet	10000 feet	50 hours @ 4 knots
Slocum Glider	5 feet	8.5 inches	3000 feet	> 30 days

a. REMUS-100, Woods Hole Oceanographic Institute

Remote Environmental Monitoring Units (REMUS) is a man-portable vehicle created by the Woods Hole Oceanographic Institute (WHOI) and is one of the smallest UUVs operated by the Navy. The small size of the system allows for single operator deployment without the need of a sophisticated (or expensive) launch and recovery apparatus. One current military application of the REMUS-100 is MCM operations by the Explosive Ordnance Disposal (EOD) community. A user evaluation was conducted as part of their procurement strategy for Program Executive Office Littoral Mine Warfare (PEO LMW) from 2001 – 2003, uncovering important lessons learned and operational capabilities explicit for very shallow water (VSW) MCM. Logging over 250 hours in 150 missions, the EOD team's UUV Platoon was able to gain confidence in the equipment and confirmed operational suitability prior to deploying the vehicles during Operation Iraqi Freedom (OIF) (Clegg & Peterson, 2003).

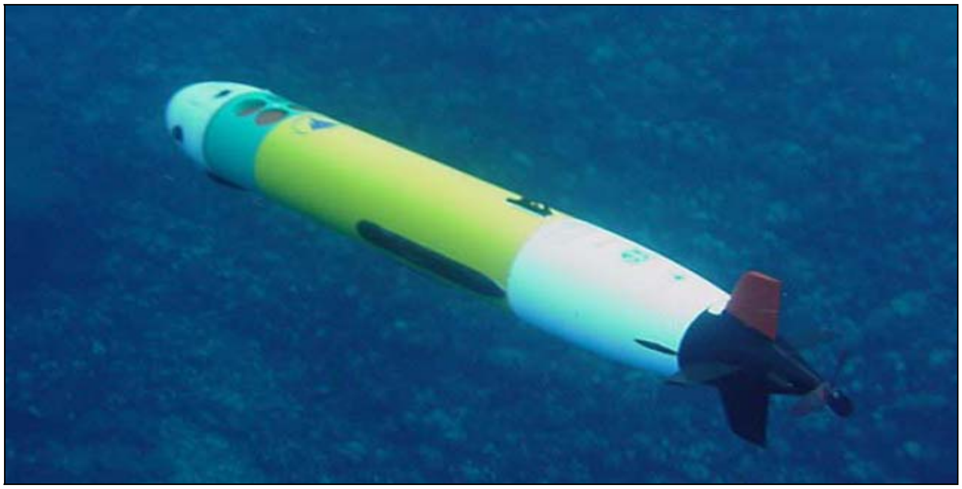

Figure 2. REMUS 100 vehicle in use by the Navy EOD community in VSW MCM testing (From: Clegg & Peterson, 2003)

b. Bluefin-21, Bluefin Robotics

Designs of military applications of UUVs are often focused toward those with 21-inch diameters. This size is the same as a mark-48 torpedo and can often be visualized best by the future UUV operators, as well as has an immediate benefit of being able to be launched and recovered from a torpedo tube (though technologically this feat is much more difficult than the average sailor would assume). The main appeal of the 21-inch diameter UUV, however, is in regard to its logistics. The handling and maintenance of this size of vessel is well understood and has been in practice for several years, which has made it very common for both industry and military applications. One example is the Bluefin Robotics Bluefin-21 Autonomous Underwater Vehicle (AUV) and the military follow-on of the Battlespace Preparation Autonomous Underwater Vehicle (BPAUV). The original Bluefin-21 design consists of modular variable length payload design on a common hull and was based on the Atlantic Layer Tracking Experiment AUV, which was used in seafloor surveys throughout the Arctic basin (Bellingham, et al., 2000). The systems have a unique feature of battery modules which allow for quick (<2 hour) turnaround deck time between its 18-hour deployments. When the BPAUV was produced for Fleet Battle Exercises, the modular design was replaced with common payloads necessary for bathymetry and bottom classification in battlespace preparation missions (Bluefin Robotics, 2009).

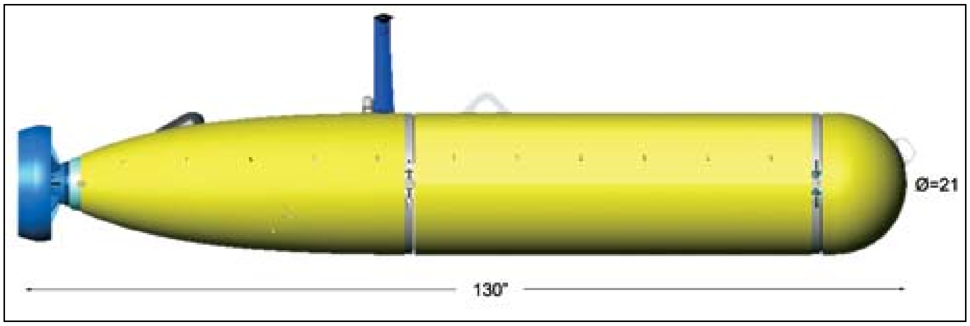

Figure 3. Schematic of Bluefin-21 BPAUV (From: Bluefin Robotics, 2009)

c. ASM-X, DCNS

A militarized similarity to the Bluefin-21 BPAUV is the ASM-X. Developed by the French defense contractor DCNS, the ASM-X has been designed with F21 torpedo requirements, allowing the UUV to be launched and recovered from submarine torpedo tubes. Once deployed, it increases the operational capability of submarines by covertly gathering and transmitting real time intelligence information collected during its patrol. The modular design of the vessel allows for ease of maintenance and dynamic performance by swapping onboard payloads (DCNS, 2010).

Figure 4. ASM-X in a laboratory broken into modular components (From: DCNS, 2010)

d. HUGIN 3000 AUV, Kongsberg

Because of their ability to endure, the Navy has been driving away from the smaller displacement UUVs and into the realm of the HWV and Large classes. The HUGIN 3000, developed in Norway, is a proven commercial UUV that is being militarized for various European navies. A large-scale vessel such as this gives the Navy the ability to reach deep seas (up to 10,000 feet) in a reliable, covert fashion. In order to be successful for USN operations, the vessel would have to be modified to military specifications. The team at C&C technologies, who currently use various HUGIN vessels for commercial mapping, believes that a militarized variant of the HUGIN 3000 would be ideal for the variety of missions being pursued by the Navy, including surveillance, mine reconnaissance, and weapons delivery (Kleiner, 2004).

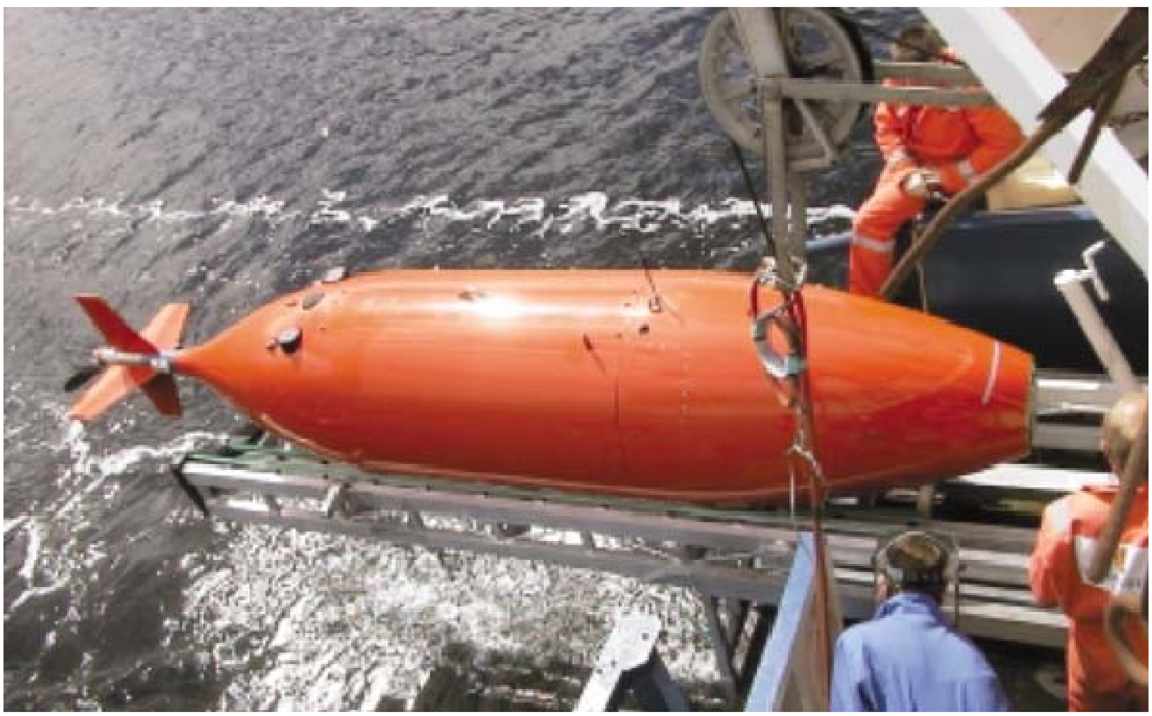

Figure 5. HUGIN 3000 shown on the recovery platform (From: Kleiner, 2004)

e. Slocum Glider, Webb Research Corporation

Propeller-less glider technology varies from traditional UUV technology. Often referred to as underwater flight, gliders rely on varying vehicle buoyancy for

forward motion, constantly propelling forward while maintaining a "saw-tooth" depth pattern. This motion decreases the accuracy of the vessel movements, but increases the endurance drastically. Additionally, during each periodic surface the glider is able to communicate mission data and obtain navigation coordinates via the global positioning system. Payloads can be varied in gliders, but current systems do not focus on military operations and consist of conductivity, temperature, and depth sensors. An overall CONOPS graphic showing the vehicle motion and communication can be found in Figure 6 (Teledyne Webb Research, 2010).

Slocum gliders, produced by Webb Research, have two different designs, electric and thermal. The electric gliders use alkaline batteries to change buoyancy and have ranges up to 1500 km and endurance of around 30 days; thermal gilders use a thermal engine making the range over 40,000 km and theoretical endurances of five years (Teledyne Webb Research, 2010). Naval applications would most likely push toward the electric technologies, but in either case, gliders produce the endurance benefits the Navy desires while keeping size, maintenance requirements, and operating costs low.

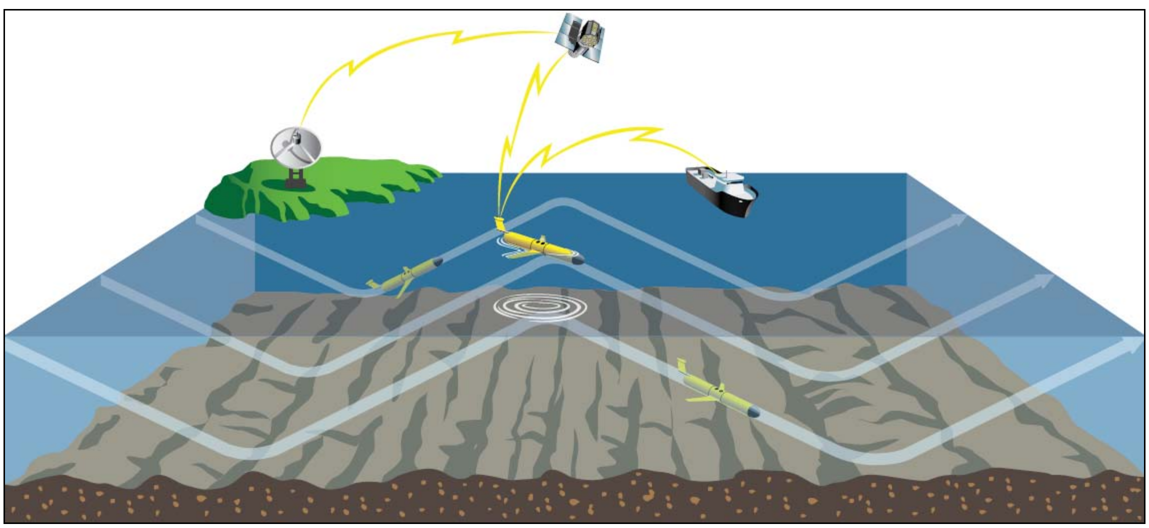

Figure 6. Slocum electric glider high-level mission CONOPS (From: Teledyne Webb Research, 2010)

3. Levels of Autonomy

There are six levels of autonomy in a vehicle, as defined by the Office of Naval Research (ONR) Uninhabited Combat Air Vehicles Program (National Research Council, 2000):

- **Fully autonomous.** The system requires no human intervention to perform any of the designed activities across all planned ranges of environmental conditions.
- **Mixed initiative.** Both the human and the system can initiate behaviors based on sensed data. The system can coordinate its behavior with the human's behaviors both explicitly and implicitly. The human can understand the behaviors of the system in the same way that he or she understands his or her own behaviors. A variety of means is provided to regulate the authority of the system with respect to human operators.
- **Human-supervised.** The system can perform a wide variety of activities once given top-level permissions or direction by a human. The system provides sufficient insight into its internal operations and behaviors that it can be understood by its human supervisor and be appropriately redirected. The system cannot self-initiate behaviors that are not within the scope of its current directed tasks.
- **Human-delegated.** The system can perform limited control activity on a delegated basis. This level encompasses automatic flight controls, engine controls, and other low-level automation that must be activated or deactivated by a human and act in mutual exclusion with human operation.
- **Human-assisted.** The system can perform activities in parallel with human input, thereby augmenting the ability of the human to perform the desired activities. However, the system has no ability to act without accompanying human input.

- **Human-operated.** All activity within the system is the direct result of human-initiated control inputs. The system has no autonomous control of its environment, although it may be capable of information-only responses to sensed data.

Complications with undersea communications and sight make human-operated, human-assisted, and human-delegated operations of a UUV to have extremely limited capabilities. Human-supervised and mixed initiative control is possible through a tethered undersea vehicle, but is outside of the scope of this thesis. This means that, ideally, a UUV program would utilize a fully autonomous vehicle, but this is one of the technical challenges currently faced by the Navy and the industrial developers. Though the technology does exist, it requires the confidence of the operator moving forward. This thesis will assume that the UUV systems discussed will have the ability to operate under a fully autonomous mode. This distinction is often made by using the phrase AUV, opposed to a Remotely Operated Vehicle (ROV), but will apply to the phrase UUV throughout this thesis.

In an unmanned system, an increase in the mission autonomy will cause an increase in the amount of system complexity. The relationship between the two is shown in Figure 7, where “Mission autonomy” is a factor both of mission complexity and the degree of autonomy, placed on a generic scale between 1 and 10. (National Research Council, 2005).

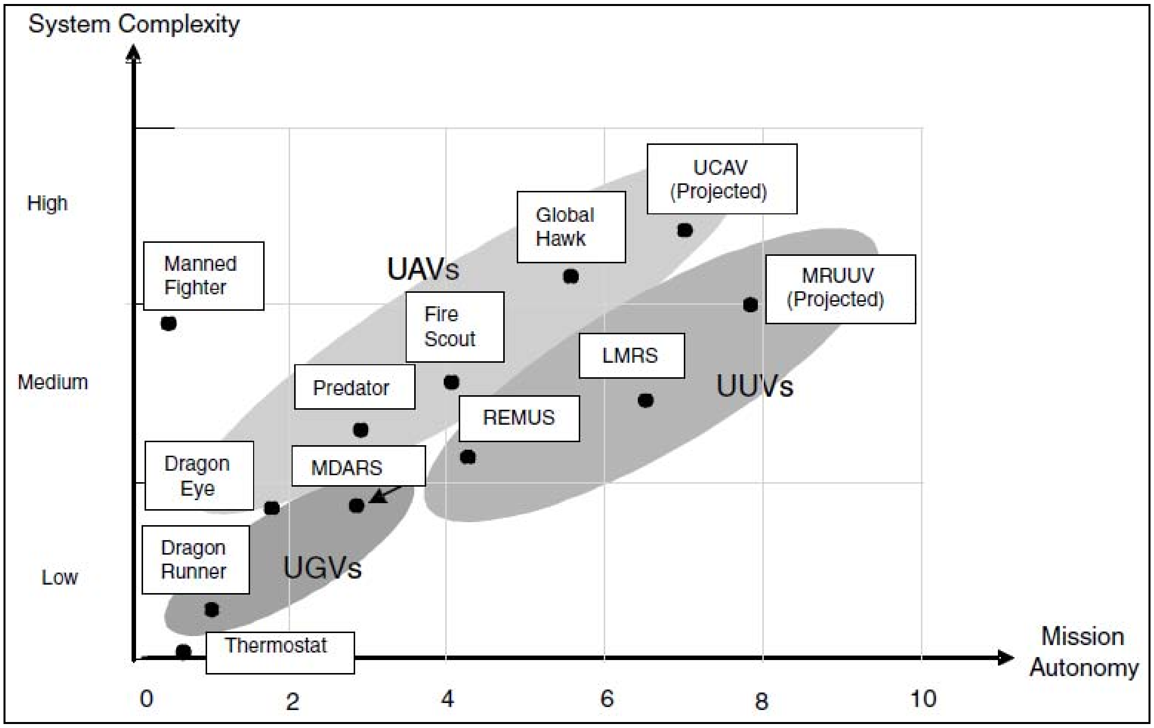

Figure 7. Relationship between mission autonomy and system complexity for unmanned systems (From: National Research Council, 2005)

With advances in technology, it is possible in the long run to see a leveling out of the system complexity with an increase of mission autonomy. This can be noticed in the figure above by the lessened degree of complexity for UUVs compared to UAVs. This reduction in system complexity can be attributed to the higher degrees of autonomy in UUVs with fewer communications (which are relatively complex) between the platform and the host vessel / operator (National Research Council, 2005). Additionally, there is a sizeable decrease in the complexity of balance and control in an undersea platform travelling at less than ten knots versus a flying platform travelling at several hundred knots.

These facts are helpful to understand when a Systems Engineer uses the level of mission autonomy (and thus system complexity) as a design choice. System design is an iterative evaluation of requirements and CONOPS given a varying set of design inputs. In the case of an unmanned vehicle, the degree of autonomy capability is a direct input to the design of the command-and-control system (C2S), mission management system (MMS), and vehicle management system (VMS), shown in Figure 8 (National Research

Council, 2005). The autonomy, subsystem, and vehicle capabilities should be equally traded to maximize the overall mission and system capability, as determined by the Systems Engineer (in the case of Figure 8 it is determined in the example shown by mission effectiveness, vehicle survivability, and system affordability).

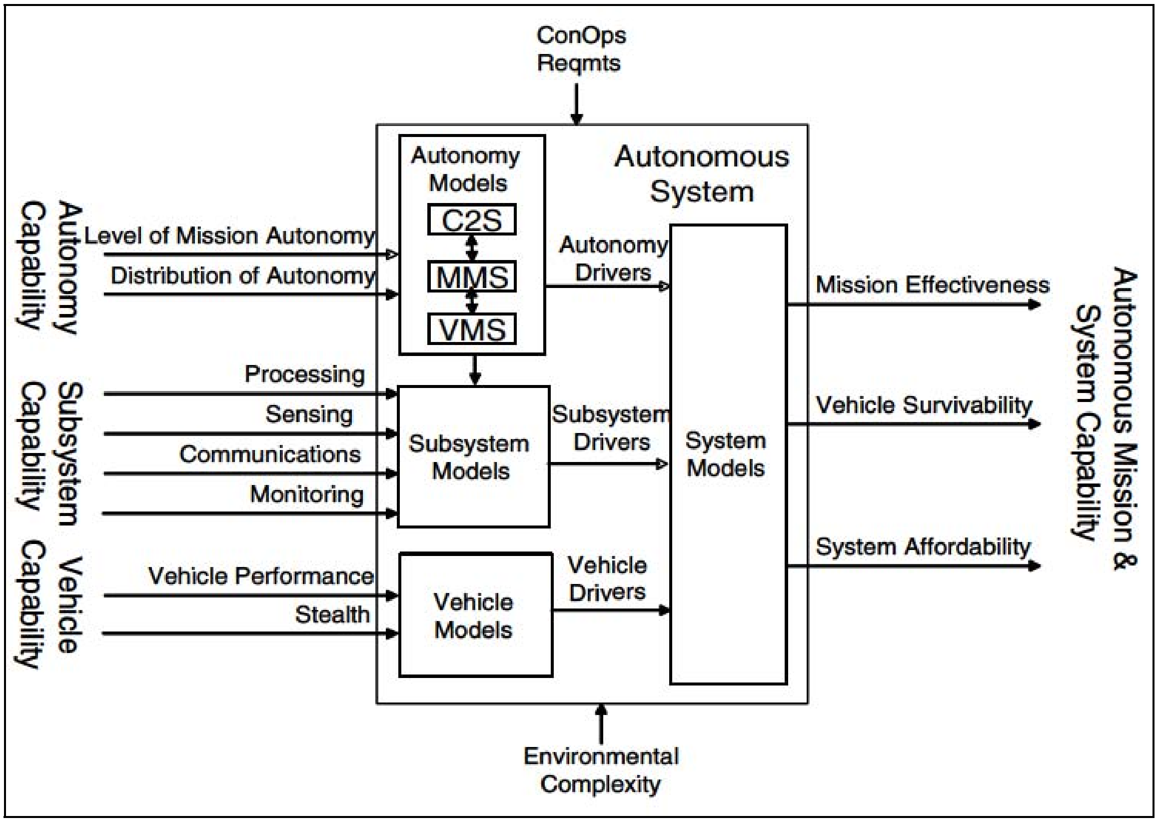

Figure 8. A trade-off study methodology incorporating level of mission autonomy as a design choice (From: National Research Council, 2005)

A successful UUV system must be designed with high levels of autonomy, and therefore with large degrees of complexity. Though this topic is not discussed in great detail in this thesis, this and other trade studies must be fully completed when creating a successful submarine UUV program. A further discussion of trade studies appears in Chapter V.

D. CHAPTER SUMMARY

This chapter reviewed the 2004 Navy UUV Master Plan and cited the nine sub-pillar missions, vision of Sea Power 21, and the four vehicle classes. Various industry

UUVs were introduced to set a foundation for the types of systems and capabilities that will be possible for use by the military. The COTS systems cited in this chapter will be revisited during the Systems Engineering chapter. Little discussion in this thesis will focus on the levels of autonomy beyond the short discussion in this chapter, and all systems will be assumed to operate in a fully autonomous mode.

The sample UUV platforms are not intended to provide any recommendations for specific vehicles or imply that these vehicles adhere to military standards. The next chapter will focus on which missions and vehicles are most applicable for use by the submarine force.

III. UUVS IN SUPPORT OF SUBMARINE MISSIONS

A. INTRODUCTION

The ability to perform missions undetected and maintain global dominance through threat deterrence makes submarines a vital asset to the Navy's Fleet. As UUVs become more popular for use by the DoD, it only makes sense to combine their missions with the missions currently completed by submarines. The construction of the Virginia Class submarines, and the conversion of the SSBNs to SSGNs, opens the door to many missions that can heavily involve unmanned systems. This chapter will discuss some of the possible missions that combine UUVs and submarines and present some of the past and present Navy programs that have merged UUVs with submarines.

B. SUBMARINE UUV MISSIONS

Future naval battles will rely heavily on advantages gained through the combination of strategies, tactics, procedures, and technologies called network-centric warfare and implemented through the strategy of ForceNet. These ideas rely heavily on Joint Force assets working together with common communication nodes. Large-scale undersea networks, like those adhering to ForceNet, will be used heavily in the future of USW, with UUVs acting as crucial communication nodes to and from submarine and surface assets. The following subsections will outline three different submarine missions and the future involvement UUVs will have with those missions. Each of the three missions (ISR, Communications, and ASW) can be evaluated as part of the overall ForceNet image.

Many missions may require the submarine to have the ability to launch and recover a UUV, but this is not a necessary factor in analyzing the possible mission sets. Currently, launch and recovery efforts have been possible via torpedo tubes and vertical launch tubes, but none of the missions discussed in this thesis require this to happen. Moving forward in the militarization of UUVs, it is important to remove the "platform-centric" thinking of programs and analyze how systems can interact with other systems.

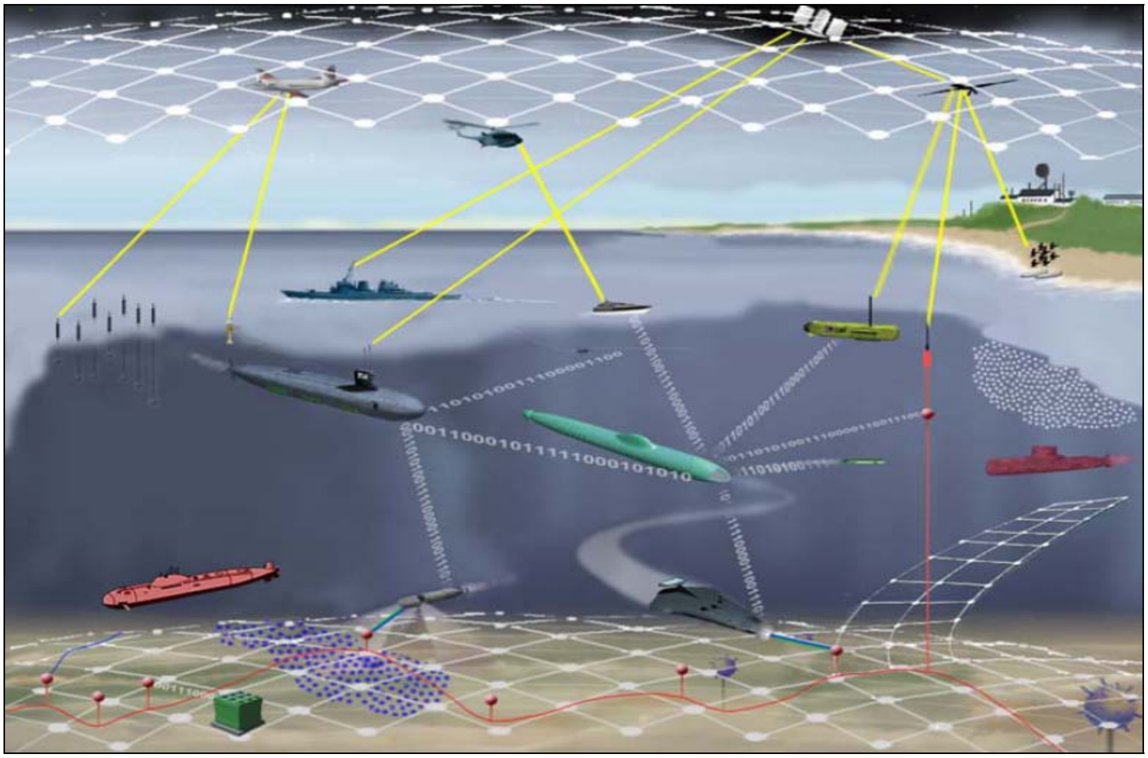

Figure 9. ForceNet concept showing network-centric connectivity to various undersea assets (From: Department of the Navy, 2004)

1. Intelligence, Surveillance, and Reconnaissance

One of the many examples of applying ForceNet to ISR for the submarine force is through a program titled Persistent Littoral Undersea Surveillance Network (PLUSNet), a multi-institution effort combining key government assets via ONR and Space and Naval Warfare Systems Command (SPAWAR). PLUSNet is an unmanned systems approach to undersea surveillance that involves the use of mature technologies. The system involved an autonomously processed cable-free nested communication network with fixed and mobile sensor nodes (Martin, 2005).

In any ISR example, including PLUSNet, there are four fundamental tasks necessary to complete the mission: collect, communicate, process, and act. These tasks are performed in various different ways by a number of unique systems (both manned and unmanned). In the case of UUVs, however, one vessel has the ability—given the appropriate payloads—to perform all four tasks on board. One UUV can include sensors

that collect the data, a platform that communicates and processes the data, and an implementer on board that takes action via movement, external communication, or weapon deployment (Fletcher, 2001). This concept is currently the main focus of UUV platform development for the Navy, namely a single, multi-payload UUV that can handle long (greater than 30 days) ISR missions.

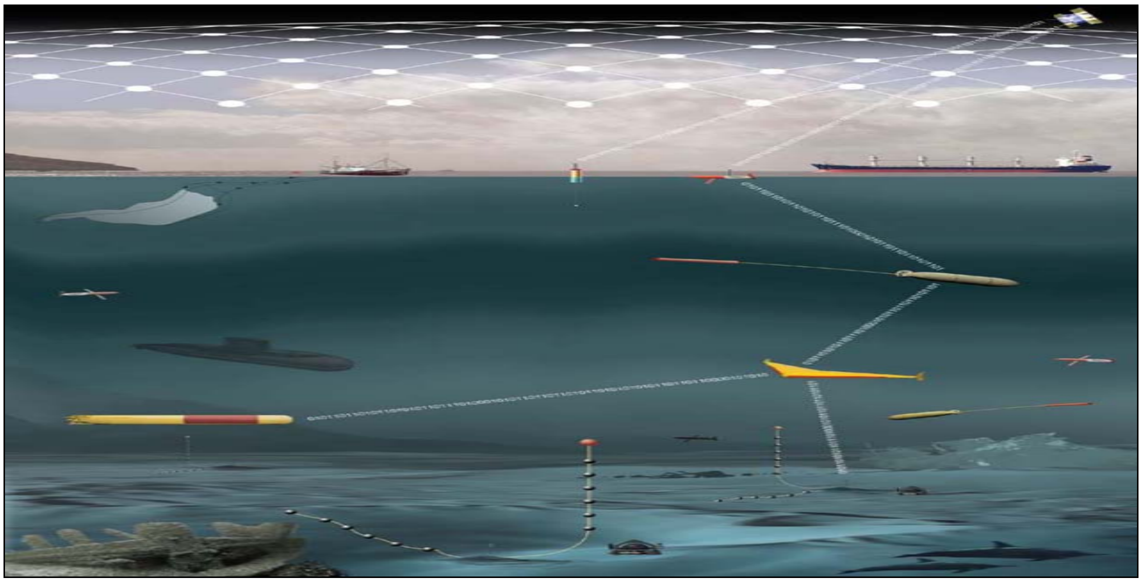

Figure 10. Operational concept of PLUSNet (From: Martin, 2005)

However, one UUV does not have to have all three systems (sensor, platform, and implementer) on board to perform the tasks, as is the case of collaboratively networked UUV groups. Instead of having one large scale UUV with multiple payloads performing multiple missions, the groups of small UUVs would include single payloads performing individual missions. These UUVs would then communicate data amongst themselves and/or a larger node (either a separate UUV or manned vessel) to gain a common operational picture of the battlespace. Currently, DARPA has given some funding to develop grouped UUV programs, but this is not the main focus of the submarine force.

In both cases, unmanned systems add a strategic advantage to the war-fighter and will allow friendly forces to gather ISR information from locations otherwise currently inaccessible or of high risk to manned systems. Possible ISR missions using these strategies include (Department of the Navy, 2004):

- Persistent and tactical intelligence collection
- Chemical, biological, nuclear, radiological, and explosive detection and localization
- Near-land and harbor monitoring
- Deployment of leave-behind surveillance sensors or sensor arrays
- Specialized mapping and object detection and localization

In one example of persistent and tactical intelligence collection, a single SSGN could deploy one or more UUVs a safe distance from the shoreline and sit out of harm's way while they patrol harbors, collecting ISR data and eventually returning to the host platform to refuel, upload data, and receive necessary operator level maintenance. This mission will free up valuable time for the submarine and the Special Operating Forces (SOF) on board to perform other valuable missions. Ultimately, due to the simplistic nature and emerging technologies, the submarine ISR mission-set will see the first full scale use of UUVs.

2. Communications

Communication is an important aspect for all military operations. UGVs and UAVs have distinct advantages of being able to easily communicate large amounts of data over long distances in air. Underwater communications, however, are not quite as simple and pose many problems in the area of USW. One solution to the problem of undersea communication is a concept called "Seaweb." Seaweb uses battery-limited sensor technology to set up a wide-area network with expendable network nodes. In an article entitled "Enabling Undersea ForceNET with Seaweb Acoustic Networks" in the *Biennial Review 2003*, author Joseph Rice of SPAWAR San Diego concluded that:

> Undersea, off-board, autonomous systems will enhance the war-fighting effectiveness of submarines, maritime patrol aircraft, amphibious forces, battle groups, and space satellites. Wide-area sensor grids, leave behind multi-static sonar sources, mine-hunting robots, and AUVs are just a few of the battery-powered, deployable devices that will augment space and naval platforms. (Rice, 2003)

In this concept, communication between non-tethered UUVs and submarines are provided via underwater digital acoustic communications (ACOMMS). ACOMMS is a short-range, modem-like communication method that is often left unencrypted (though it could easily be encrypted). In 2005, Seaweb ran three experiments using their expendable node technology to aid in the navigation of several types of UUVs. These tests showed that undersea ACOMMS technologies using multiple scattered nodes are a viable solution for naval communication. The next step for Seaweb will be to utilize the sensor nodes to communicate to and from UUVs and submarines, as well as relay mission specific information to and from satellites via various surface assets, as shown in Figure 11 (Rice, 2005).

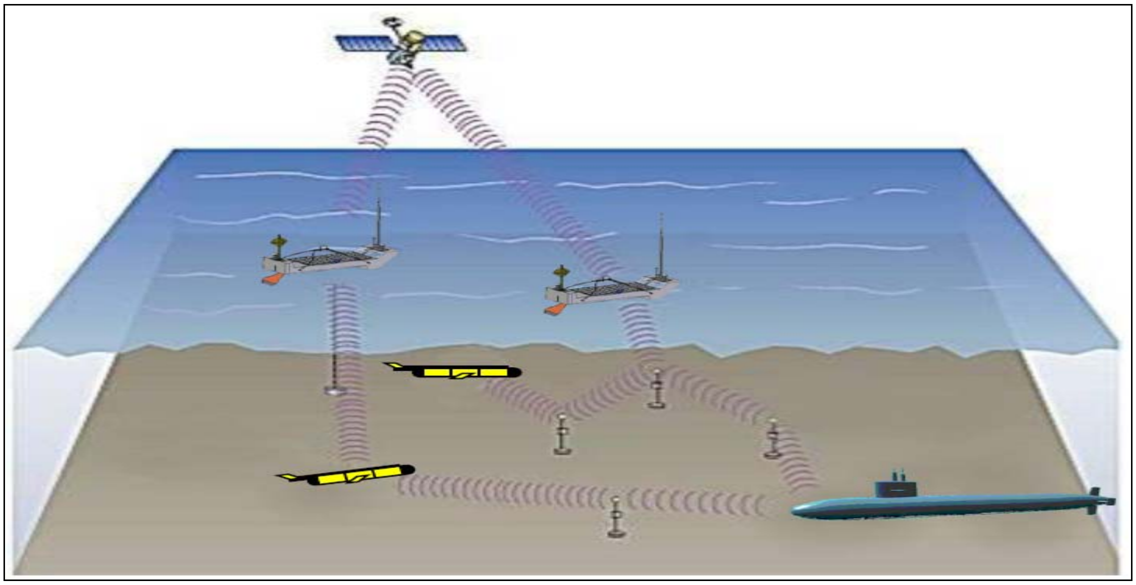

Figure 11. Seaweb acoustic communication and navigational network model (From: Rice, 2005)

A downside of the Seaweb concept is the necessity to set up a complex undersea communications network in unfriendly waters. In the future, the application of submarine launched systems will allow these networks to be setup covertly. The next step in a program will be to utilize groups of UUVs as the communication nodes. There are multiple programs being worked on by industry that utilize this theory and have the ability to perform the desired missions.

3. Anti-Submarine Warfare

The continuing submarine threat ensures ASW is a key component of maintaining dominance of the sea. Though some ASW tactics use surface and air assets to detect, track, and engage undersea threats, the submarine has always played a vital role in assisting in deterring the enemy. As the enemy moves the battles closer to shore and engages in littoral warfare, the current tactics of war fighting change. In an attempt to understand this threat better, Task Force ASW has instituted a new focus on littoral ASW and identified three distinct categories of ASW, outlined in Table 5 and shown in Figure 12 (Department of the Navy, 2004).

Table 5. Task Force ASW nomenclature with descriptions (After: Department of the Navy, 2004)

Nomenclature	Description
Hold at Risk	Monitoring all the submarines that exit a port or transit a chokepoint.
Maritime Shield	Clearing and maintaining a large Carrier Strike Group (CSG or ESG) operating area free of threat submarines.
Protected Passageway	Clearing and maintaining a route for an ESG from one operating area to another free of threat submarines.

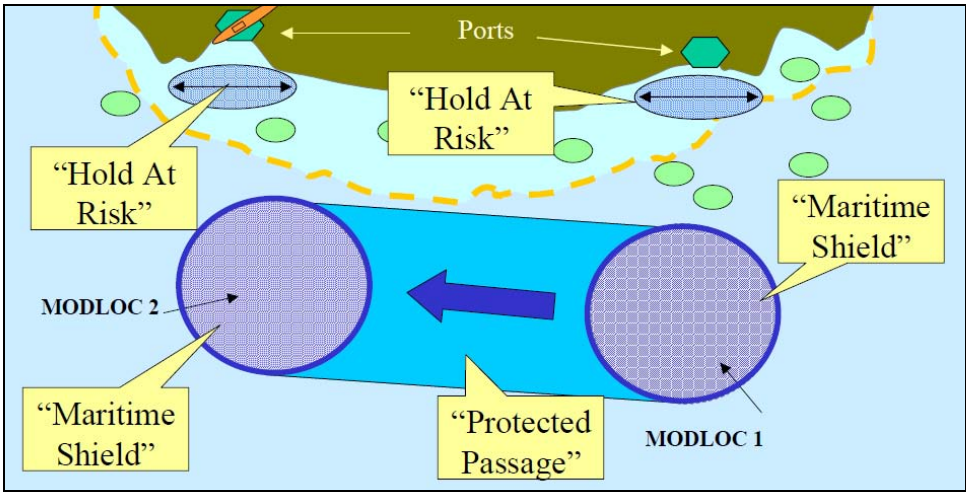

Figure 12. Task Force ASW model depicting nomenclature (From: Department of the Navy, 2004)

UUVs can prove useful in all three categories described by Task Force ASW, but will have the greatest impact in the "Hold at Risk" scenario. The force multiplication factor added by UUVs will allow them to constantly patrol barrier choke points at low speeds and monitor harbor traffic (Button, Kamp, Curtin, & Dryden, 2009). The general concept for this scenario is to launch the patrolling UUVs from a surface vessel, such as LCS, and allow them to travel to the "Hold at Risk" location undetected. Submarines can aid in this operation by deploying the UUVs from closer in shore, still remaining undetected but cutting down on the transit time and energy loss of the UUVs.

While on location, the UUVs have three possible variations of the "Hold at Risk" mission. They could (Department of the Navy, 2004):

- Employ non-lethal weaponry
- Employ lethal weaponry
- Accumulate intelligence information about threat submarines (both individually and collectively)

These variations could change, however, if the UUV is in communication with a friendly submarine. Instead of making the determination locally whether to employ weaponry (lethal or not), the UUVs could communicate using underwater acoustics with the nearest SSN, allowing the decision to be made on board and relayed back to the UUV. Additionally, the UUVs and friendly submarines could remain in constant communication, relaying valuable mission and classification data, drastically increasing the overall effectiveness of the Task Force ASW approach. Unfortunately, there are severe limitations in the bandwidth and range of ACOMMS, rendering its technology more of a risk than a benefit (in most cases).

C. PAST AND PRESENT NAVY SUBMARINE UUV PROGRAMS

Currently there is no formal UUV program of record relating to submarine operations. There have been, however, programs of record that have been cancelled due to various reasons. These extinct programs can provide useful insight into how the systems will affect the lives of sailors on board submarines. In this section, four

different UUV programs will be succinctly discussed to provide a background and lessons learned for the manning and maintainability requirements of future UUV programs.

1. Near-Term Mine Reconnaissance System

The Near-term Mine Reconnaissance System (NMRS) was a contract that was awarded to Northrop Grumman Ocean Systems via a sole source proposal. Leveraging off of existing work done by Northrop Grumman, the NMRS was a two-vehicle platform that was originally tested by the Navy in 1998. The two vehicles were the same diameter and slightly shorter than a mark-48 torpedo and were able to be launched and recovered from a single SSN torpedo tube. The NMRS proved the ability to utilize basic autonomous operation while using a fiber-optic tether link to the submarine to send the information gathered by its forward and side looking sonar arrays.

The program was originally designed with a very limited set of requirements to be an immediate, simpler solution for a submarine UUV program. The program showed a lot of promise of successfully operating an autonomous vehicle launched from a SSN, but the funding for it was cancelled to support the Long-term Mine Reconnaissance System (LMRS) program.

2. Long-Term Mine Reconnaissance System

When the NMRS system was announced, the Navy also announced plans to produce a LMRS with a larger set of requirements than its predecessor. After a time-consuming three-phase down-select process, the contract was awarded to Lockheed Martin with the intent of a service date of FY 2005. The program ultimately did not meet the requirements given by the Navy and was cancelled, but it is a good example of a UUV program with a solid set of operational requirements.

The initial Operational Requirements Document (ORD) for the LMRS specified a threshold/objective sortie reliability of 0.93/0.96 for a 40-hour mission. This reliability included performing all mission critical activities (preparation, launch, mission, recovery, and post-mission activities) without a mission critical failure. Additionally, there was a

specified threshold/objective for sortie launch availability of 0.86/0.92. The manning and maintainability aspects of the LMRS were also clearly defined in the ORD. For maintainability and logistics support, the LMRS was given the requirement to support a 6-month submarine patrol and do so with a 20-year operational life. The system needed to be comprised of preventative and corrective maintenance measures at organizational, intermediate, and depot level maintenance facilities, while utilizing ship's force and shore-based maintenance activities whenever possible. Lastly, the system was to be operated by a dedicated cadre of less than 10 individuals, augmented by ship's force (Federation of American Scientists, 1996).

The LMRS failed due to problems with the launch and recovery mechanisms not being as reliable as needed to perform the critical missions demanded of the system. The program ultimately was cancelled. Unfortunately, the valuable lessons learned by Lockheed Martin during the development have not been properly passed on for use by future programs. Additionally, perhaps due to the shortcomings of the NMRS and LMRS programs, the Navy has moved away from the primary focus of a UUV launched and recovered from a torpedo tube.

3. Mission Reconfigurable UUV

A spin-off of the LMRS program was the Mission Reconfigurable UUV (MRUUV) program. This program had the intent of using a common UUV body with multiple modules containing specific payloads that can be varied to run different missions, and was scheduled to enter the fleet in 2008. One main requirement of the MRUUV was that it had to have the ability to share a common launch and recovery system with the LMRS; the problems with the LMRS trickled down to the MRUUV program. Although the program had a lot of potential for completing ISR missions and creating a mission-flexible UUV, it was cancelled in 2008 due to lack of funding.

4. Current Projects

Since the Navy does not have a formal submarine UUV program of record it has, instead, various projects that it is working on through different research funding sources and managed by the Advanced Development Office (ADO). The new way of thinking is

to adapt existing platforms in use by industry or research organizations and develop them for military use. Some benefits of the Navy using development and research organizations for funding are that the systems can be developed without formally defining missions or requirements and it puts the systems in the hands of the operators to gain their confidence and trust moving forward. The downside, which has proven to be true with relation to the current submarine UUV programs in development, is that after a system passes the developmental tests it was designed for, there is no future funding line to keep the project active. This causes systems that prove themselves feasible to lack future development into formal programs.

a. Sea Stalker

The Sea Stalker UUV is a spinoff of the original Sea Horse UUV program and is a product of the Pennsylvania State University Applied Research Laboratory (PSU ARL). The Sea Stalker is a 38-inch diameter platform with a speed of nearly 5 knots. The Sea Stalker UUV has proven developmental testing while being launched and recovered from the USS Bainbridge (DDG-96) and is projected to be submarine deployable from a dry deck shelter (DDS) on a SSGN (Kenny & Belz, 2008). The Sea Stalker is designed for ISR and command and control by using a set of retractable antennas to combine stealth and functionality. A downfall of the Sea Stalker program is power; due to submarine restrictions, it cannot use lithium battery technology and is currently supplied by alkaline (D-Cell) battery technology. The future of the Sea Stalker program is not known, but it has shown some technological capabilities that are possible from a DDS deployable UUV.

Figure 13. Monopole retractable antenna concept as used in the Sea Stalker UUV (From: Mullins, 2009)

b. Sea Maverick

The Sea Maverick UUV is another PSU ARL project. The Sea Maverick is larger and faster than the Sea Stalker – 48-inch diameter with a top speed approaching 15 knots while submerged. This increase in size changes the functionality completely as it is no longer able to be launched via a submarine DDS, therefore requiring a support ship, like LCS, or a complex redesign for a SSGN D5 missile tube launch. In September of 2009 the Sea Maverick UUV completed operational testing with the Joint Interagency Task Force (JIATF) South off the coast of Key West, Florida. The UUV was deployed using the NAWC 38 Ranger class support ship operated by the Naval Air Systems Command (NAVAIR) and maintained mission support communications via satellite with JIATF South (United States Southern Command, 2009). The reports of the system performance show that it was a successful test and the operators have high hopes for the future of the Sea Maverick system.

Figure 14. Sea Maverick UUV shown on launch crane during JIATF South exercise (From: United States Southern Command, 2009)

c. Other Projects

Though it is no longer a primary focus, the Navy has not completely moved away from the smaller, torpedo tube launched UUVs. Various projects are being worked on but are beyond the classification level of this thesis. Some concepts include a torpedo tube launched AUV similar to the ASM-X used by the French Navy, on which would remain tethered to the submarine for instantaneous data transfer for ISR. Because of complications with the recovery of the system, it can be left behind or recovered by a platform similar to LCS.

D. POSSIBLE SUBMARINE / UUV INTERACTIONS

There are many different roles for the submarine when working in tandem with a UUV. It is a common misconception that a program involving submarines and UUVs will require the submarine to play an important role is all aspects of the mission of the UUV. Though ideally this would be the case, it is more realistic to look at the incremental interactions between submarines and UUVs. This section will outline a few of the various interactions that could exist between the submarine and UUV.

1. Launch and Recovery

Ideally, a submarine would be able to both launch and recover a UUV. There are several options to consider for how to manage a system that can both launch and recover

UUVs, including 1) torpedo tubes (conventional or oversized), 2) hangars (DDS or wet deck), 3) vertical launch tube (D5 or other), and 4) piggy back.

The two most commonly documented ideas are via a conventional torpedo tube and DDS. Though the LMRS was unable to develop a reliable recovery arm for a UUV, the technology is still feasible and Figure 15 shows an example of an attachment that could be added to a conventional torpedo tube to be used for both launch and recovery. This example, similar to the original LMRS design, would use homing and docking sonar guides to recover a UUV onto a recovery arm built into one of the four torpedo tubes (Hardy & Barlow, 2008).

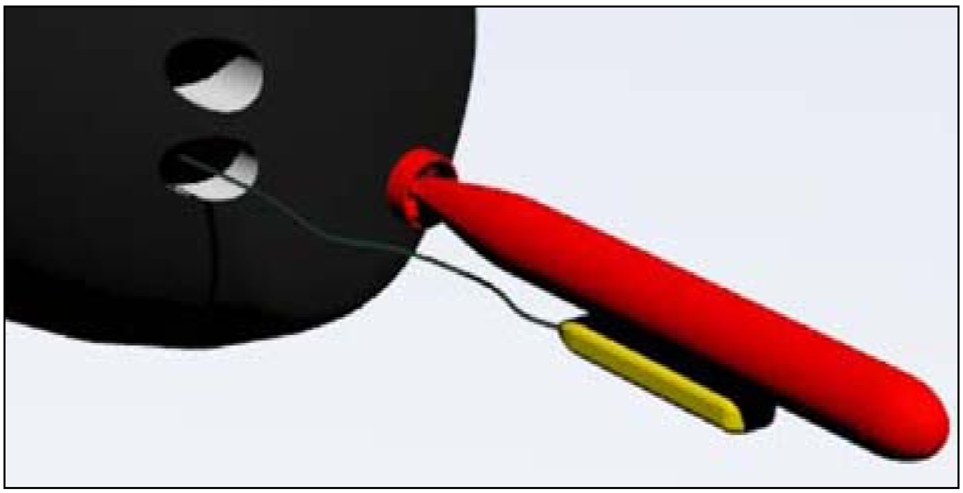

Figure 15. Visualization of UUV recovery via a single conventional torpedo tube (From: Hardy & Barlow, 2008)

The technical challenges behind successfully recovering UUVs into torpedo tubes is not the only reason the Navy is not pursuing this technology. The torpedo rooms of a Los Angeles- and Virginia-class submarine have only four torpedo tubes and the use of one tube (or more) for UUVs would severely limit the capability of the submarine during a wartime scenario. Additionally, space in the torpedo room is very limited and any equipment necessary for the UUVs would further limit the amount of torpedoes that can be kept on-board. These and other disadvantages, as well as advantages, of using a torpedo tube launched UUV are outlined in Table 6.

Table 6. Key advantages and disadvantages of using a conventional torpedo tube for UUV launch and recovery (After: Hardy & Barlow, 2008)

Key Advantages	**Key Disadvantages**
– Permits multiple types of 21 inch torpedo type UUVs to be deployed – Assuming recovery can be undertaken then UUV maintenance, recharging and payload reconfiguration activities are made easier inside the submarine in a clean, dry environment. When not in use the UUV is stored dry and safe. – Potentially minimal impact on the overall submarine design in terms of arrangement and arguably easier to retrofit the system to an existing submarine. – Potential to utilize existing torpedo discharge systems. – Allows covert UUV deployment. – Less risk of aborted UUV recovery fouling submarine propeller	– Constrains AUV design to 21 inch torpedo design with consequential endurance and payload capacity constraints. – If recovery is required, recovery system will most likely take up capacity of at least one torpedo tube (unless modular recovery system design is employed that can be retrieved into the weapons stowage compartment). – Additional stowage’s required in the weapons stowage compartment. – Recovery is arguably more difficult when submarine is in transit.

Due to the importance of torpedoes and the robust design of the current forward end of a submarine, a redesign of the torpedo room to accommodate for UUVs is not an option. Fortunately, for the future development of UUVs, SOF missions have incorporated the use of the DDS on Los Angeles-class submarines, starting with the USS Dallas (SSN-700) in early 2000 (Rehana, 2000). Since their deployment, these external hangars have been discussed, developed, and tested for use with UUVs. If it is the intent of the Navy to have a submarine both launch and recover a UUV (or group of UUVs) the viable near-term option is most likely to be a DDS, though it does come with some major disadvantages, including reducing capability of the host submarine (increased signature, reduced maneuverability, etc.), as shown in Table 7.

Figure 16. Dry deck shelter on back of Los Angeles-class submarine (From: Rehana, 2000)

Table 7. Key advantages and disadvantages of using a dry deck shelter for UUV launch and recovery (After: Hardy & Barlow, 2008)

Key Advantages	Key Disadvantages
– Permits larger and greater range of AUVs to be deployed Dry CMH weight will almost certainly preclude fitting of CMH on smaller submarines. – UUV maintenance, recharging and payload reconfiguration activities made easier inside the DDS. – When not in use the AUV is stored dry and safe. – Likely to be able to retrofit such a system to an existing submarine of sufficient size – Potential to build in most DDS and UUV support systems to allow for fast fitting to submarine – Could be designed to support transfer of human maintainers between main pressure hull and DDS to undertaken maintenance tasks, etc – UUV deployment and recovery system could be simpler	– DDS is likely to require complex drain down and flood systems, air and pressure management systems, etc. – Safety justification is likely to be harder if divers are required to work in and outside the DDS. – Recovery is arguably more difficult when submarine is in transit. – Does not allow covert UUV deployment. – Impacts on submarine signature and maneuverability, etc. – Potential fin wake effects for L&R whilst in transit.

2. Launch Without Recovery

A short-term solution to having a successful submarine UUV program will be to separate the mechanisms for launch and recovery. Whether it is from a torpedo tube,

missile tube, or DDS, having a submarine complete only the launch portion of the mission will incorporate the benefits of a quick, stealthy deployment while avoiding the technical challenges faced by recovery at speed and depth. Additionally, the lack of submarine recovery will avoid the drawback of space considerations to support organizational level maintenance.

There are two options to consider for the recovery portion of the experiment:

- **Abandonment.** This method is costly and controversial, but would be ideal for situations where the data collected by a UUV is crucial, but the risk of recovery is too great. The UUV system would need to have some form of "self destruction" in order to maintain the security of the collected data and types of technologies used. Though there are few missions that would call for abandonment as a primary end state, it is a procedure that should be considered in the background of most sensitive UUV deployments in case the primary mode of retrieval does not work – including operations in which the UUV could be entangled in the undersea environment (i.e., fishing nets and reefs).
- **Support Ship.** A method being considered by the USN is the use of a support ship, such as a Destroyer or LCS, to recover a submarine-launched UUV after its mission has been completed. Prior to recovery, the UUV will bury itself into the seafloor, hover, or surface, waiting for a recovery signal from the support ship.

3. Non-physical Interactions

It is possible for a submarine UUV program to be successful without any physical interaction amongst the two entities. In this case, the UUVs would need to be deployed from a support ship or directly from land. Regardless of the form of deployment, there are several possible non-physical interactions between the submarine and UUV, including mission control, consumer and interrogator of data, and docking station delivery.

The mechanism for launch and recovery will play a vital role in the set of missions able to be accomplished by a UUV program, but each of the interactions discussed above hold true for all forms of UUV launch and recovery. Designing UUV and submarine interactions independent of the launch source will help transition to a less "platform centric" design of UUV systems. When systems can be designed without the platform in mind, there is more room for growth and an increased chance of long term success for a program.

a. Mission Control

In the near-term, it is unlikely that a UUV will be fully autonomous and able to complete its entire mission with no communication back to an operator. Instead, it is more likely that the UUVs would operate under the "fixed initiative" level of autonomy. Similar to the way UAVs are operated, UUVs will be able to perform a majority of their functions autonomously, but will need to remain in communication with an operator to provide and update critical mission data.

As discussed earlier, undersea communications are more difficult than those faced by UAVs in the air and UGVs on the ground. With the exception of physical linked communications, such as fiber optic links, successful non-acoustic undersea communications require short distances between the transmitter and receiver. In covert situations, a submarine operation in the area of interest (AOI) may be necessary to ensure short distance communications. Though the concept is well understood, it is not well studied. Submarines should be viewed as the top method of mission control in forward UUV operating areas, even if the system was not launched from the submarine.

b. Consumer and Interrogator of Data

There are instances where submarines will require the valuable data collected from a UUV, but not be in control of the UUV. In these cases, the submarines will consume and interrogate the data sent from the UUV. One example of this involves in the mine detection mission. Currently, MCM missions are the focus of many non-submarine UUV programs. In these programs, the UUV patrols the AOI and returns to a predetermined set point. The data collected is manually downloaded by the operator

through a data-link between the system and laptop computer where it is then analyzed as necessary. With relatively slight advances in technology, these programs can evolve to include sending the data to a submarine for consumption and interrogation by the crew aboard the submarine. Removing the "middle man" will increase the efficiency of the area search and provide the submarine crew with important tactical data in as short of a time as possible, without the maintainability or manning responsibility of many of the proposed UUV programs.

c. Docking Station Delivery

The two greatest technical challenges of a UUV program are endurance and underwater communications. One theory that can both add to the longevity of a UUV deployment and increase the bandwidth of communication to and from the UUV is the use of a submerged docking station. Various systems have different theories on the technical features of the dock and some systems only perform one of the functions, but in all cases the high level theories remain the same.

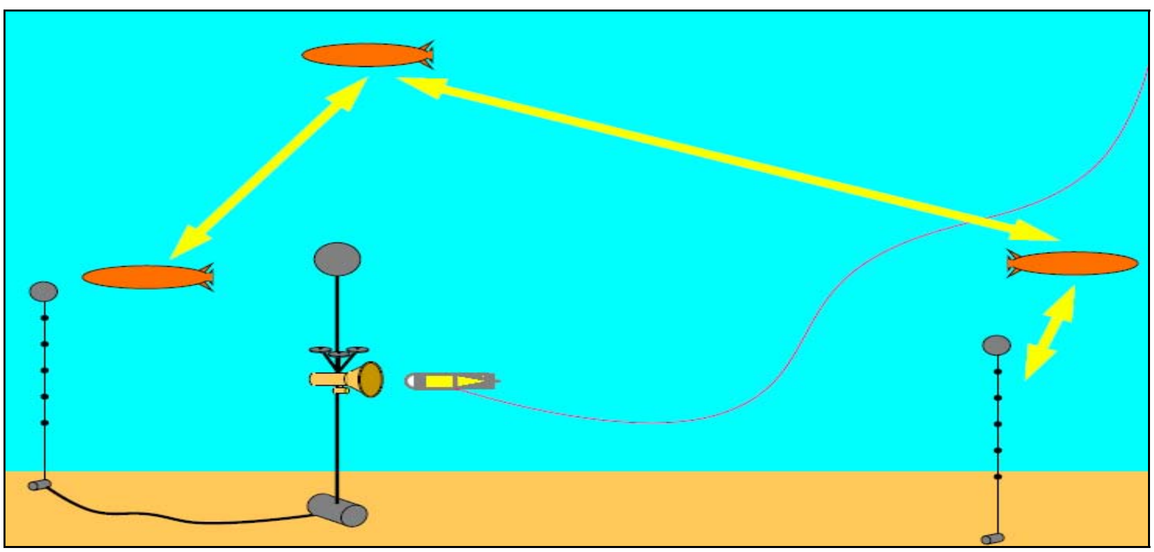

Figure 17. Flying plug attaching to a communications dock (From: Cowen, Briest, & Dombrowski, 1997)

One SPAWAR program that combined both charging and communication into the same docking station was a mid-90s program entitled Distributed Surveillance Sensor Network (DSSN). Experiments were conducted to prove the feasibility of a

“flying plug” concept, where a tethered ROV would dock into a communication station and relay high bandwidth communications over fiber-optic networks. The flying plug would complete a link between the host platform, generally a submarine, and all entities attached to the fiber optic network (Cowen, Briest, & Dombrowski, 1997).

The concept of the flying plug has great advantages that are beyond the scope of this thesis, but what it does provide is some proven undersea docking technologies. Branching from the flying plug technology, the DSSN project used a low cost Odyssey AUV developed by the Massachusetts Institute of Technology. The DSSN experiment, performed in Buzzard’s Bay, MA proved the ability to perform an underwater docking for a small scale UUV by way of three different guidance methods: optical, magnetic, and acoustic (Cowen, Briest, & Dombrowski, 1997). More importantly for this thesis, the experiments showed the feasibility of a low cost undersea dock for charging and data communication.

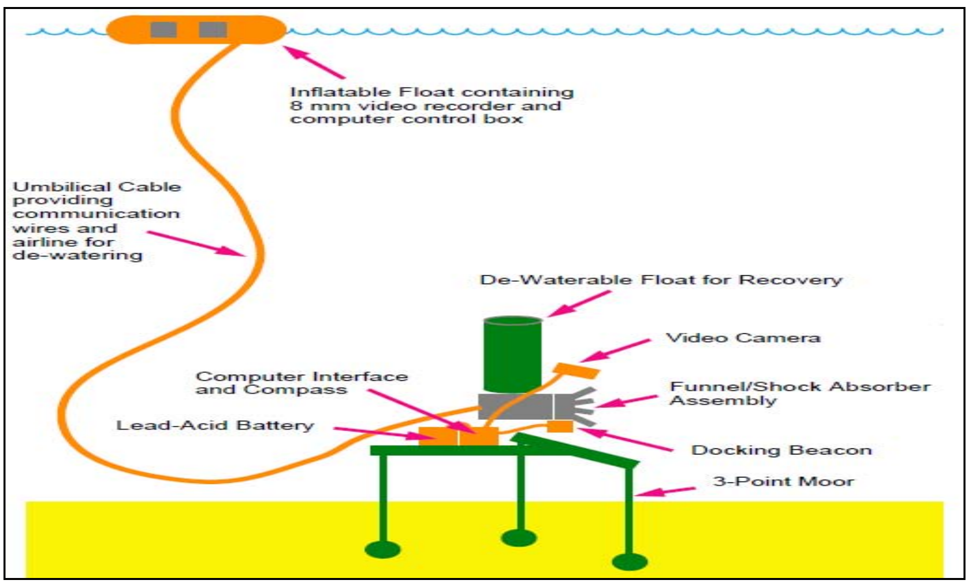

Figure 18. Docking station and remote interface used in DSSN experiment (After: Cowen, Briest, & Dombrowski, 1997)

Moving forward with the DSSN concept, a submarine could deliver a docking station, similar in concept but more advanced in technologies, to the one shown in Figure 18, allowing a UUV deployed in an enemy AOI to utilize the docking station for either charging or communicating or both. The use of a forward deployed docking

station would be able to keep UUVs in forward locations longer while allowing mission supports assets, such as submarines and surface vessels, to remain outside of high risk areas.

E. CHAPTER SUMMARY

It is important to note that this chapter was written with classification levels in mind. It was not intended as a teaching point of the vast missions of UUVs and submarines, but as a background to the ideas of the important role UUVs will play when they are in tandem with submarines. Pertinent areas of the interactions section will be revisited during the systems engineering section. The missions and programs discussed in this chapter will be further analyzed in the Systems Engineering discussion.

IV. APPLICABLE LESSONS LEARNED FROM UGVS AND UAVS

A. INTRODUCTION

UGVs and UAVs have been in use longer than UUVs. This longevity provides the UGVs and UAVs with valuable lessons learned that can be applied to their undersea counterparts. Additionally, as shown in a report of the budgets of the DoD in FY2007-2013 in Figure 19, unmanned maritime systems (UMS) as a whole are set to receive far less funding than their airborne unmanned counterparts (Button, Kamp, Curtin, & Dryden, 2009). To maximize use of the small budget, applicable lessons that can be translated from UAVs and UGVs to UUVs can have a sizable impact on technological development in the undersea domain.

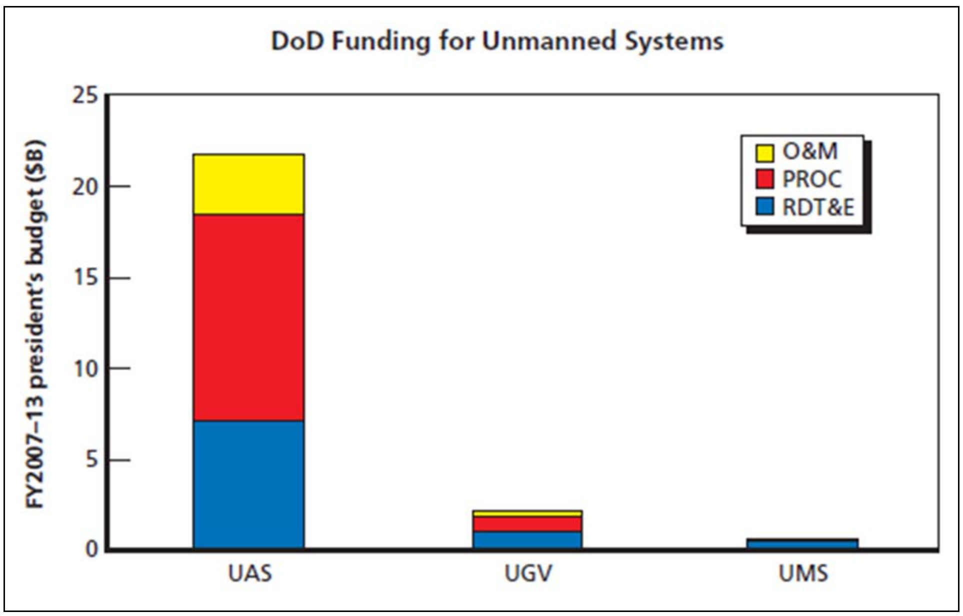

Figure 19. FY2007-2013 DoD Funding for unmanned platforms (From: Button, Kamp, Curtin, & Dryden, 2009)

This section will review a brief history of UGVs and UAVs, discuss their similarities with UUVs, and provide several lessons that can be applied toward the manning and maintainability aspect of UUVs in support of submarine missions. Each of the eleven lessons learned are summarized quickly and will be used in support of the

conclusions of this thesis. Not all lessons learned can be applied in the same manner. Additionally, not all lessons learned will be applicable to all UUV systems.

B. UNMANNED GROUND VEHICLES

1. Brief History of the UGV

The development of UGVs with nontrivial capabilities has its roots in the late 1960s with the first major development of the “Shakey” system. Though “Shakey” faced challenges with the autonomy aspect and was considered a failed program, the system started the mobile robot baseline. The 1980s would see the outdated program evolve into the Defense Advanced Research Projects Agency (DARPA) program Autonomous Land Vehicle (ALV). With a goal of using a realistic environment for research, the ALV demonstrated artificial intelligence in mobile robots for military use. The Army’s look at UGVs in the 1980s transitioned to use by the Department of the Navy by including Reconnaissance, Surveillance, and Target Acquisition (RSTA) applications funded by the Naval Ocean Systems Center, in conjunction with Marine Corps research. Similar to modern UUV applications, RSTA programs provide battle space awareness to mission commanders from behind enemy lines. Today, all branches of the DoD have UGV programs spanning a variety of missions from disposing of bombs and transporting gear to performing maintenance and gathering intelligence (Gage, 1995).

2. Similarities Between UGVs and UUVs

Modern UGVs and UUVs face similar technological development challenges. Figure 20 shows six key areas for UGVs and further breaks down autonomous behavior. This figure could easily replace the center block UGV with a UUV and have the same meaning (National Research Council, 2002). This similarity leads to the potential of many areas of overlap in progression of both technologies.

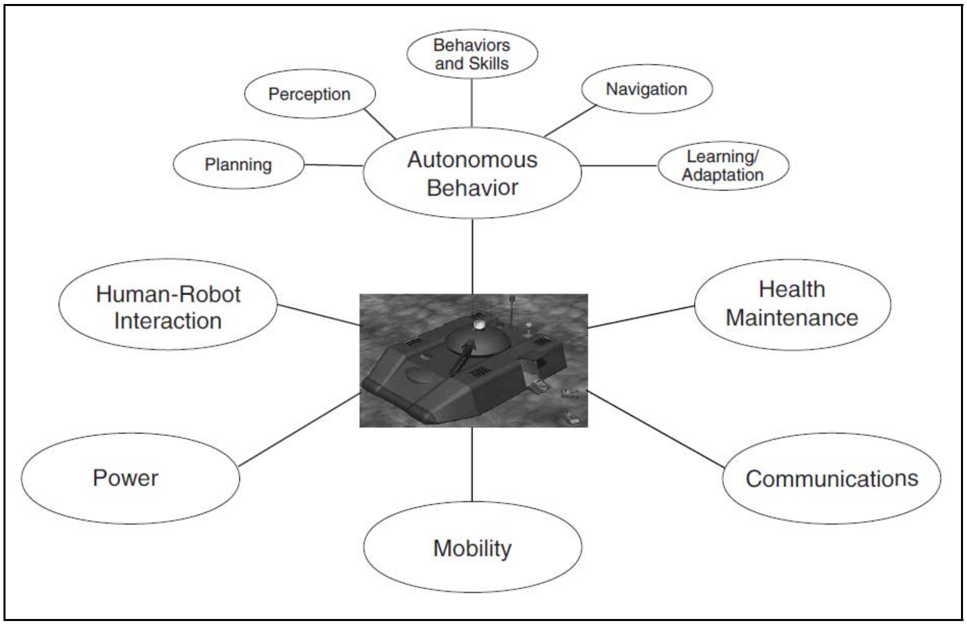

Figure 20. UGV technology areas (From: National Research Council, 2002)

Beyond the functional commonalities, the development cycle and mission sets for future UGVs are similar to UUVs. In a publication for the Army titled "Technology Development for Army Unmanned Ground Vehicles," the National Research Council postulates four example systems of UGVs for Army development. The four systems discussed in great detail in the article are 1) a small robotic building and tunnel searching vehicle ("Searcher"), 2) a small-unit logistics mover ("Donkey"), 3) an unmanned wingman ground vehicle ("Wingman"), and 4) an autonomous hunter-killer team ("Hunter-Killer"). These four examples, summarized in Table 8, are linked to sample capabilities and missions (edited below to include missions most analogous to UUVs) in a similar style to the different classes of UUVs currently being developed for the Navy.

Table 8. UGV example systems, capability classes, and potential mission applications (After: National Research Council, 2002)

Example System	**Capability Class**	**Possible Applications**
Searcher	Teleoperated ground vehicle	Mine detection/clearing, ordnance disposal, soldier-portable reconnaissance/surveillance
Donkey	Semiautonomous preceder/follower	Supply convoy, battlefield support, reconnaissance/surveillance, physical security
Wingman	Platform-centric autonomous ground vehicle	Remote sensor, counter-reconnaissance, single outpost/scout, battle damage assessment
Hunter-Killer	Network-centric autonomous ground vehicle	Deep RSTA, combined arms, static area defense, reconnaissance

Not unlike UUVs (or ROVs in some cases), each example system has various levels of human control and support as shown in Table 9. The human control of the example UGVs, however, is significantly different from the planned use of UUVs for the Navy. Underwater communications (especially those at speed and depth) are not as simple and straightforward as on land line of sight communications. This difference does change the relationship the operator can have with the platform in a UUV (vice UGV), that does not fully discount the similarities between the two systems.

Table 9. Human control, human support, and health maintenance for the example UGV systems (After: National Research Council, 2002)

System	Human Control	Human Support	Health Maintenance
Searcher	– Control by joystick or touch screen – Continuous control for planning and navigation	– Maximum of one operator and one maintenance technician per Searcher	– High physical reliability, low maintenance
Donkey	– Program electronic paths to be followed – Load and unload cargo – Monitor communications	– Maximum of one supervisor and two maintenance technicians will be able to operate a small (10-12) donkey team	– High physical reliability, low maintenance – Cooperative diagnostics for remote operator – Ability to know when to call for help
Wingman	– Direct new locations while en route – Monitor sensors and other inputs – Actively make go or no-go decisions – Electronically direct/override movements	– No more than one assistant section leader (controller) and one maintenance technician	– Design for combat survivability – Algorithms for self-diagnosis
Hunter-Killer	– Program various initial inputs (movement, communications, intelligence, …) – Monitor communications for situations requiring human guidance – Override in case of changes in situation	– Control is by on-duty staff officer at headquarters – Non self-repair maintenance done by small groups (<10 personnel) to support up to five teams (10 killers, 50 hunters each)	– Self-repair by reconfiguring components – Self-repair by self-reprogramming

3. Lessons Learned from UGVs

The relatively mature nature of UGVs provides some lessons learned in the deployment of UUVs for submarine related missions. In 2001, SPAWAR San Diego published a technical report "Unmanned Ground Vehicle (UGV) Lessons Learned"

which related UGV lessons to UUVs for MCM in the EOD community. The “Top 10” issues found during their study were broken into three main categories: operations, programmatics, and technologies as shown in Table 10 (Blackburn, Laird, & Everett, 2001). The highlighted portions of the chart have been summarized below as the three major lessons learned that apply to submarine missions from a manning and maintainability standpoint, and a fourth lesson independent of the “Top 10” list is added at the end.

Table 10. Top 10 issues compiled from UGV lessons learned for MCM UUVs (After: Blackburn, Laird, & Everett, 2001)

Category	**Top 10 Issues**
Operations	*Uncertainty promotes survival**
	*Many simple cooperating agents are superior to one complex agent**
	New technology forces changes in operations
Programmatics	Understanding between the user and the developer is critical
	Understanding the technology is cost-effective
	*Simpler solutions provide better foundations**
Technologies	Integration is not easy
	Communications are not dependable
	Automaticity is not autonomy
	The road from teleoperation to autonomy does not exist

**Issues used for UGV Lessons 1-3*

a. UGV Lesson 1: Uncertainty Promotes Survival

Regardless of the mission of an unmanned system, it needs to be designed to be reliable and survivable. A robot designed for combat survivability, whether a UGV, UAV, or UUV, will have the ability to last in the harsh war, or war-like, operational environments. Fortunately, the random nature of unmanned control allows for unpredictable maneuvers, formations, and behaviors, which provide advantages in hostile environments (Blackburn, Laird, & Everett, 2001). Though this random behavior will, as a result, decrease the chance of attrition kills (those resulting in a complete loss of the system) of the UUV, they will also increase the chance of mission abort kills (those resulting in an incomplete mission, regardless of cause). The take-away here is that the

operators will need to understand the benefits in uncertainty and will need to be trained to balance it to assure success in the tactical settings.

b. UGV Lesson 2: Simpler Solutions Provide Better Foundations

A simple solution is often neglected because it does not address all of the system requirements. Fundamentally, a simple solution does not have to address all of the requirements, as long as it does not violate any of the unaddressed requirements. Being that requirements are generally independent of one another, multiple simple systems can be integrated together, if each addresses different requirement sets. An example of this was addressed in the SPAWAR team's 2001 interview with Albert Bradley of WHOI. Discussing the issue of power capability, Mr. Bradley stated:

> Most AUV designs are limited by power available. This comes out in the first "back of the envelope" design cycle. Those projects that then panic and go to the handbooks to choose "the best power source" rarely allocate enough effort to taming the exotic choice they came up with. There are enough problems to face, start a new AUV design with a simple power source. When it's working, then you can update the power system. (Blackburn, Laird, & Everett, 2001)

The end state of the simple system approach may be more practical in a UGV than in a UUV, but it can be utilized in the developmental stages of a new system. Addressing requirements incrementally will give operators invaluable experience with the systems and give the war-fighter confidence when the more complex system is deployed in the future.

c. UGV Lesson 3: Many Simple Cooperating Agents are Superior to One Complex Agent

UGV operators utilize many simple vehicles as a "strength in numbers" approach which is different than the advantages this approach gives to the undersea warfare communities. Though the Navy's decision to shy away from smaller, simpler UUVs has been made from a technical capability standpoint (mainly energy density and payloads), the concept of using smaller, networked UUVs should not be lost.

The advantages of smaller UUVs make them a valuable asset. First, in all measures there is less cost per platform and potential further savings with "economy of

scale" during production. Second, less maintenance support is necessary; this is very applicable to submarine operations, as the UUVs can be replaced opposed to repaired (though the logistics of this may be daunting). Next, there are fewer critical components. As system reliability is a function of critical component reliability, reducing the number of these allows for increased reliability through redundancy and simplicity (Blackburn, Laird, & Everett, 2001). Last, the major concern with small UUVs is power and fuel; though larger UUVs can have longer durations and ranges, the cooperation of the small contingencies can offset this disadvantage.

There are times where a complex agent is a better application than many simple cooperating ones. Prior to technologies being proven, similar to what is described in "UGV Lesson 2," the use of a multitude of simple and collaborative systems should be the preference. After the technology has matured, larger and more complex systems can and should become the priority of the stakeholders. Ultimately, the system complexity should be considered in a formal trade study, as discussed in Chapter II.

d. UGV Lesson 4: Maintenance Should Be Done at the User Level

UUV systems, like UGVs, should be designed with line replaceable units (LRUs). The use of LRUs does not replace the contractor, as they will still manufacture the parts, perform advanced levels of maintenance, and provide long-term logistical support. Additionally, LRUs minimize the contractor involvement in the maintenance, often drastically reducing the life cycle costs (Blackburn, Laird, & Everett, 2001). This is especially true with any maintenance that will be performed on UUVs while underway. Modular parts and LRUs are ideal for UUVs since sailors aboard submarines (or support vessels like LCS) have limited space, resources, and time to perform costly, complex repairs.

A formal discussion of the three levels of maintenance (organizational, intermediate, and depot) is presented in Chapter V. This section will promote the appropriate use of all levels of maintenance, focusing on more than just the user level portion. Unfortunately, especially in the case of submarines, there are size and logistical considerations that will not always accommodate user-level maintenance. The important

lesson to be understood is that a successful program will incorporate various types of maintenance and, whenever possible, the maintenance routines that can be performed at the operator level will have compounding benefits for the entire program.

C. UNMANNED AERIAL VEHICLES

1. Brief History of the UAV

The history of airplane-like UAVs for military use by Americans can be traced to the Interstate BQ-4/TDR as early at 1936. Originally starting as the Navy aircraft called "assault drones", the program originated as a suggestion for using remotely-controlled aircraft in combat (Parsch, 2005). The 1950s-1970s would see drones evolve into use for surveillance missions. Though many of these programs were promising, most were cancelled due to technical problems (Tetrault, 2010). These problems caused commanders to lose faith in UAV technology.

Figure 21. U.S. Navy photo of an original Interstate BQ-4/TDR (From: Parsch, 2005)

In 1982, the Israeli Air Force defeated the Syrian Air Force and changed the opinions of commanders toward UAVs. Israeli forces used UAVs for decoys, jammers, and enemy surveillance, allowing their manned aircraft to swiftly defeat 86 Syrian aircraft with minimal losses (Tetrault, 2010). Since then, Operation Desert Storm (1990-1991) became the stepping-stone for American use of UAVs by military forces. Modern day UAVs include fixed wing and rotary craft that are used for a variety of missions ranging between reconnaissance and surveillance of the "Global Hawk" to air-to-ground combat of the "Predator."

2. Similarities between UUVs and UAVs

The surveillance and communication nodes provided by UAV missions are similar to the needs of UUVs for the submarine force. Future UUV technologies will focus on other UAV missions beyond ISR and into the combat and combat support realms. UAVs have been developed in a wide variety of shapes and sizes, each of which, to some extent, support modular mission packages and LRUs.

Modern day UAVs face some of the same challenges as UUVs. First, UAVs are limited by their communication and bandwidth. These issues vary from the types of issues dealing with underwater communications but still have the same result in the battlefield. Second, UAVs lack intelligent autonomy and target recognition, and without complete "intelligent" autonomy in both UAVS and UUVs, they will not be used during complex missions that require extremely high confidence levels of maneuvering and target recognition. Third, operations with manned platforms pose the same problems in UAVs as UUVs; fear of collisions call in to question the safety of both platforms. Last, UAVs do not have a highly reliable recovery mechanism across all platforms; recovery of UUVs at sea poses the same setbacks as UAVs (National Research Council, 2005).

3. Lessons Learned from UAVs

The operational experiences of UAVs across all branches of the DoD have had the systems evolve drastically during OIF and Operation Enduring Freedom (OEF). This data has been thoroughly documented and is starting to be shared amongst all interested parties. UUV development can take many lessons from the struggles of UAVs over the past decade.

a. UAV Lesson 1: System Requirements Should Be Clear Up Front

"UGV Lesson 2" stated that requirements can be met incrementally. However, this does not imply that the requirements need not be stated at the beginning of the program. UAV support for OIF and OEF required the USAF to field UAVs as quickly as possible and therefore required a rapid acquisition strategy. As a result, all of the requirements were not clearly defined before design and production. This has lead to

uncertainty in the long-term support status of the aircraft (Drew, Shaver, Lynch, Amouzegar, & Snyder, 2005). This should not be the issue for UUVs as there is currently not the same rapid demand faced by the Navy as was UAVs for the Air Force. Though all requirements need not be addressed during the developmental stages of UUVs, all should be clearly stated at the beginning of a program. This lesson will be discussed in detail in Chapter V.

b. UAV Lesson 2: Acquire Reliability and Maintainability Data Throughout All Stages of Development

If the event arises, however, that a UUV system will require rapid acquisition, it will be important for researchers to take advantage of every opportunity to gather data. Reliability and maintainability data is able to be recorded and analyzed in prototypes and first generation systems, which was not done for the USAF deployment of UAVs (Drew, Shaver, Lynch, Amouzegar, & Snyder, 2005). This data is important for determining manning and supportability metrics and should be analyzed for all UUV systems tested. Additionally, UUV programs that have been cancelled will almost always have this data available and should be shared across programs.

c. UAV Lesson 3: Structure a Process for Sharing Data

The "stove-piped" programs created in the DoD often leave good sources of data unknown, or unavailable, to other programs. UAV conferences are starting to break down the barriers of information and UUVs need to follow this same direction (Drew, Shaver, Lynch, Amouzegar, & Snyder, 2005). The Navy's PEO LMW has taken the right steps in opening the lines of communication between UUV programs by the creation of the ADO, but this needs to be extended to include minor programs, other defense programs, and industry, where applicable.

From a UUV program to UUV program aspect, the data being shared should be a combination of operational and technical data. Operational data may help newer UUV programs to properly focus on missions, tasks, and functions. The technical data shared amongst the two programs is perhaps the most valuable. Discussing the success (or failure) of different sensor packages, energy sources, and data analysis

software will increase the probability of success of new programs. Additionally, there is a lot of data that can and should be shared amongst UUV programs and UAV/UGV programs. This data can also be both operational and technical, but a majority of the important lessons learned would be in the operational sense (as the technical differences between the two programs can be extreme). When possible, the Navy should look at what successful UAV programs have done for maintenance and manning challenges and lessons that can be learned. For example, some of the Navy's foremost UUV operators modeled their manning after what they discovered with the Predator UAV program. This suggestion could branch into comparing airspace with waterspace management data to find trends that will help simplify the currently complex waterspace management plans.

d. UAV Lesson 4: Limit the Number of Design Configurations

Spiral development and prototyping of UAVs have created several different configurations supported by the USAF. Each unique design complicates the support and maintenance of the UAV fleet (Drew, Shaver, Lynch, Amouzegar, & Snyder, 2005). In an effort to curb the cost of production, logistics, maintenance, and operation the Navy should rethink the UUV design and limit the number of unique platforms. The use of LRUs and modularly designed mission components should then fit the common sized components and allow a platform to perform a variety of different missions.

Creating a single chassis that can be used amongst all programs is an ideal, but probably an unrealistic expectation. Instead, the Navy should develop standards for interoperability in their UUV design. These standards should include launch and recovery design features and modular open architecture features. The standards should not be set across all UUVs, but amongst UUVs in a size / displacement group.

e. UAV Lesson 5: Consider Supportability Up Front

Supportability should be considered an important cost driver during the pre-concept design phase of a system. Operations and support (O&S) costs comprise the largest individual percentage of LCC for almost every major program. Additionally, reliability and maintainability attribute directly to the manpower calculation for unmanned systems. O&S costs cannot be avoided, so they should not be delayed

(Lockheed Martin Corporation, 2002). Many programs of record that have performed admirably during testing have been cancelled due to LCC considerations. However, these programs could have been designed better or avoided altogether if O&S structures had been considered initially.

In a submarine UUV program, the supportability can vary drastically. Chapters V and VI will discuss in more detail the different options available. These include the use of cadres of personnel to support operations as opposed to the use of ship's force and the maintenance being completed onboard a support ship instead of the submarine. There are drastic differences in the system designs that can be incorporated based on these supportability decisions, which is why they should be made early in the system development process. These options should also be included in the trade studies discussed.

f. UAV Lesson 6: Endurance Has its Benefits

The UAV experience has shown that longer sorties have resulted in less maintenance due to the reduction in number of cycles and cycle-related fatigue. Research has shown that for UAVs a 24 hour sortie length shows a significant reduction in maintenance man-hours per flight hour (assuming a similar level of maintainability), as shown in Figure 22 (Lockheed Martin Corporation, 2002). The conclusion of less maintenance for longer sorties may seem obvious, but the degree to which manpower can be reduced is an important lesson to take for UUVs.

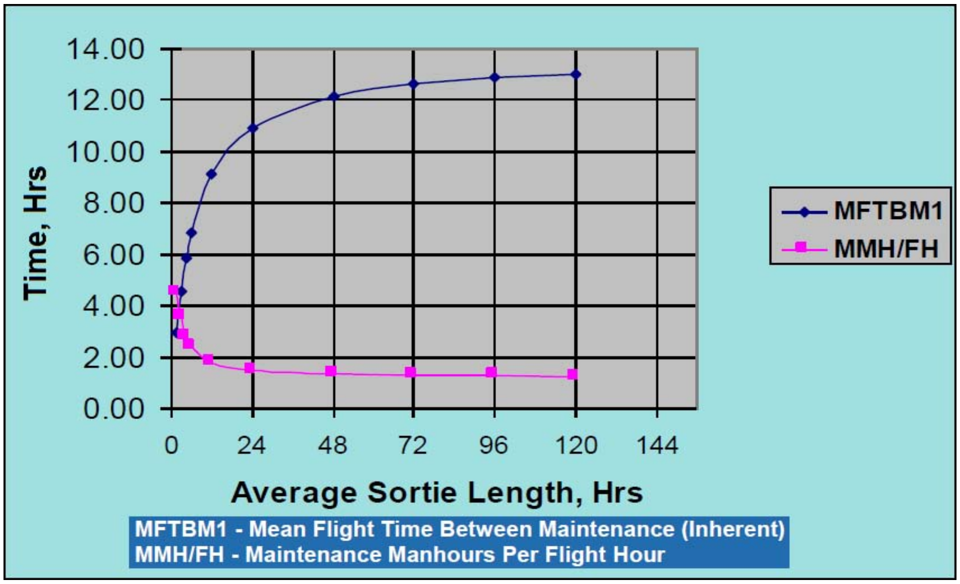

Figure 22. Maintainability data as a function of sortie length for UAVs, assuming similar levels of maintainability (From: Lockheed Martin Corporation, 2002)

UUV missions will not have the same numerical correlation to UAV missions, but the principles still hold true. Current Navy UUV missions last roughly 6-8 hours. If this number can be increased to 48 hours, or further yet to 30 days, the impact these systems will have on the manning aboard their host platform can be reduced drastically – and that is not even considering the manning to launch and recover the systems. Any time there is room to increase the mean time between maintenance (MTBM), the change should be considered in depth because of the impact it may have on supportability and LCC.

g. UAV Lesson 7: Minimize the Levels of Redundancy

"UGV Lesson 2" and "UGV Lesson 3" focused on simplifying the system to potentially reduce the amount of critical components, thereby increasing system reliability. An alternative method is to create redundancy in each critical component, ensuring that the loss of one component does not result in a loss of the system. Though redundancy increases the safety, survivability, and mission reliability, it is not without an increase in cost. In order for redundancy to be cost effective, it needs to incorporate extremely high reliability or extremely low cost. Trade studies have shown that systems that are overly redundant become more expensive than those with minimal levels of

redundancy; between 2-3 levels of redundancy is generally the most cost effective approach for UAVs, as shown in Figure 23 (Lockheed Martin Corporation, 2002), assuming a constant mean time between failure (MTBF) rate. UUV systems will have different reliability data, but the end result of trade studies should prove to have the same results, namely, that risk should be balanced when considering the levels of redundancy.

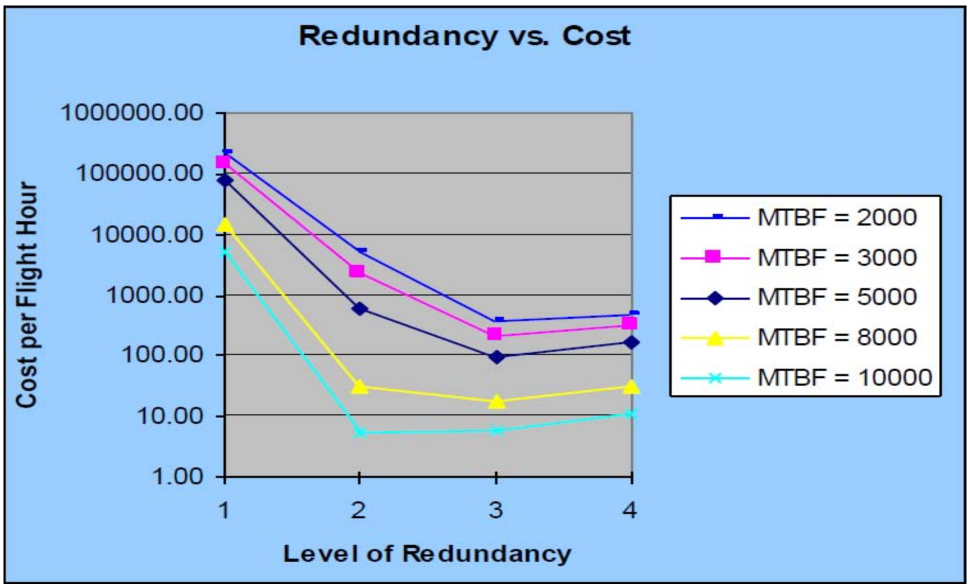

Figure 23. Relationship between redundancy and cost per flight hour for UAVs, assuming critical failure rate of 1/3 of MTBF (From: Lockheed Martin Corporation, 2002)

D. CHAPTER SUMMARY

This chapter discussed the history, similarity, and lessons learned of both UGVs and UAVs as they apply to the manning and maintainability of UUVs for use in submarine missions. It is the intent of this chapter to be a brief introduction to sample systems and neglects many aspects of UGV and UAV operations unrelated to the core research of this thesis. The eleven major lessons learned are summarized in Table 11. It is not the intent of the section to be an extensive study of UGV or UAV systems, and further research should be done for a better understanding of the unmanned systems discussed in the chapter.

Table 11. Summary of eleven UGV and UAV lessons learned for UUVs

Number	Lesson Learned
UGV 1	Uncertainty promotes survival
UGV 2	Simpler solutions provide better foundations
UGV 3	Many simple cooperating agents are superior to one complex agent
UGV 4	Maintenance should be done at the user level
UAV 1	System requirements should be clear up front
UAV 2	Acquire reliability data throughout all stages of development
UAV 3	Structure a process for sharing data
UAV 4	Limit the number of design configurations
UAV 5	Consider supportability up front
UAV 6	Endurance has its benefits
UAV 7	Minimize the levels of redundancy

V. SYSTEMS ENGINEERING AND ANALYSIS

A. INTRODUCTION

Prior to this chapter, this thesis has focused mainly on the gathering of data through literature reviews, internet-based resources, conferences, meetings, and interviews. This chapter, however, will take the ideas discussed in Chapters II-IV and discuss where they fit in moving forward with a systems engineering approach to the development of future formal UUV programs. This section begins with a definition of the systems engineering process and points out some deficiencies found in the past Navy submarine UUV programs. After discussing the systems engineering approach, there is a section focused on the manning and maintenance requirements that will need to be addressed to allow UUV systems to operate successfully with the submarine force. However, the systems engineering approach outlined here is applicable to all stages of future UUV program development.

B. SYSTEMS ENGINEERING APPROACH

Prior to laying out the specific steps necessary to make a successful UUV program, it is important to define systems engineering and give an overview to the generic approach taken by a Systems Engineer to solve a problem. This section will cover the systems engineering process, feedback, and trade studies utilized by a Systems Engineer.

1. Systems Engineering Process

One of the many methods available to understand the scope of the systems engineering process is outlined by the Defense Acquisition University (DAU) model shown in Figure 24. The model illustrates three distinct stages of converting the process inputs into outputs with continual trade studies and assessments before and after each stage (Defense Acquisition University, 2001). Though this process was created with electrical/electronic engineering in mind, it is applicable in the systems engineering of any type of system.

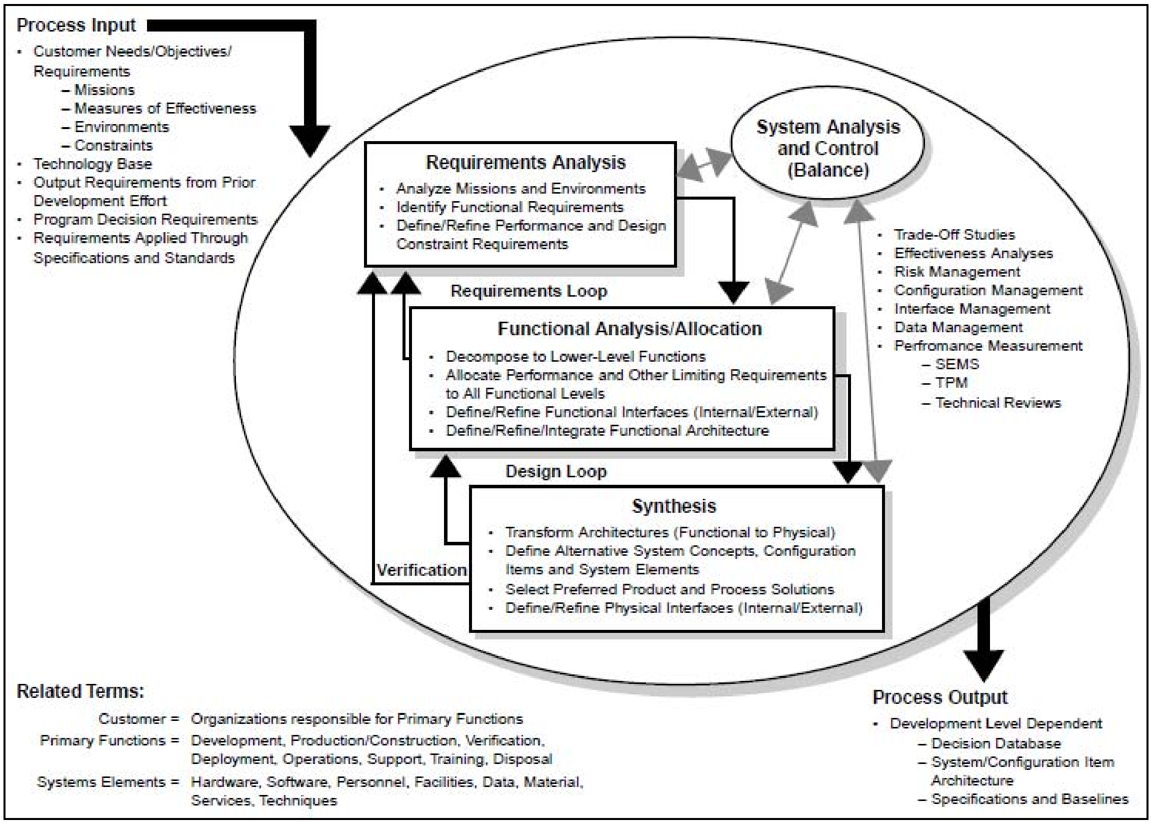

Figure 24. DAU systems engineering process model (From: Defense Acquisition University, 2001)

Combining the data presented in the DAU model and many other applicable systems engineering models, there are four fundamental stages to system design lifecycle. This four stage process has analysis, verification, and feedback occurring simultaneously with each step. All four stages are required for a program to be "Systems Engineered" correctly. To successfully complete a mission or set of missions, the four stages of the process need to occur in the following order:

- Develop Requirements, based on missions
- Determine Tasks, based on requirements
- Create Functions, based on tasks
- Design Components, based on functions

a. Developing Requirements

Government program development tends to be done differently than in the civilian world, but that does not mean that the necessity for a high-level envisioning of the process changes. When a program is created, it needs to begin by defining requirements, and these requirements should be based on the mission of the program, and not on the physical entities that the program wishes to create. This was true in the case of UAVs and "UAV Lesson 1" and should continue to remain true with future UUV programs. This means that programs should not be started with the finished product in mind.

The requirements stage is often not understood by the customer. A formally trained Systems Engineer will know the maxim associated with a customer asking an engineer to build a bridge to get across the water. Many engineers would now interpret the requirement, given by the customer, to be "build a bridge". Unfortunately for the customer and the engineer, building a bridge is not the real requirement. The real requirement is: get across the water. The system developed during the process may end up being a bridge, or it may be a ferry, tunnel, or airplane. Current UUV projects have violated this maxim of understanding the requirements.

Proper requirement definitions are produced with the system stakeholders and are derived from the mission requirements. The process is hierarchical with system, component, and configuration item (CI) requirements being derived from the originating requirements, shown in Figure 25. Many engineers consider the role of the systems engineering process begins at the ORD, when in fact the Systems Engineer should work directly with the stakeholder to understand the requirements and eventually turn those requirements into an ORD (Buede, 2000).

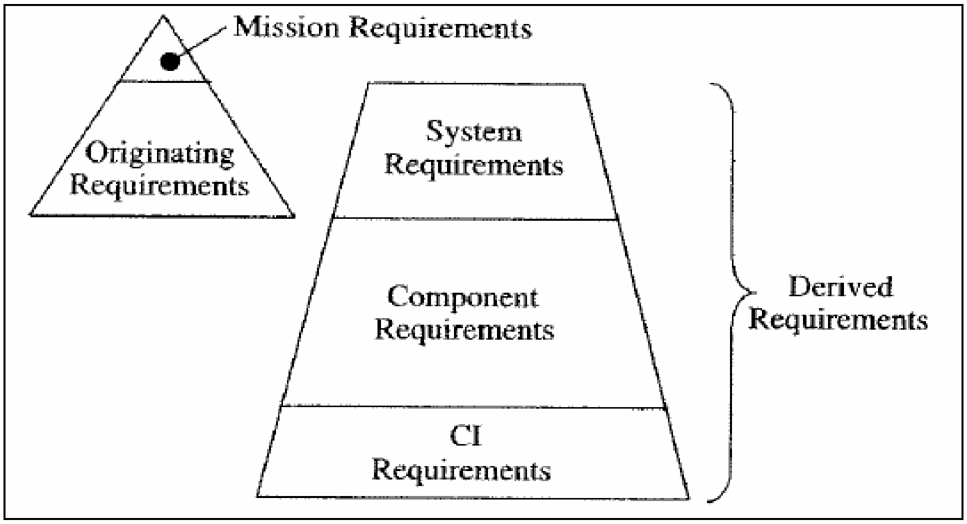

Figure 25. Hierarchy of requirements (From: Buede, 2000)

Two of the current submarine UUV projects being worked on for the Navy are the Sea Maverick and the Sea Stalker. These programs (as discussed in Chapter III) have shown success in various at sea tests, but are not part of a formal program and have included unclear, if not completely undefined, requirements. This shortfall has meant that even though the programs may have performed up to the operator's expectations, the funding line is not in place for future development of the systems and, as a result, they may be left forever sidelined.

b. Determining Tasks

After determining the system requirements, the next step in systems architecting is to determine which tasks are necessary to meet the stated requirements. In a USN system design, these tasks should be taken from the Universal Naval Task List (UNTL), a combination of the Universal Joint Task List and the Navy Tactical Task List. These extensive lists comprise of specific tasks necessary to complete missions at the operational and tactical levels. The UNTL is a hierarchical list with the nomenclature for a naval tactical level task being "NTA."

A sample tactical level task from the UNTL that may apply to UUV missions is "NTA 1.5.2.3 Conduct Undersea/Antisubmarine Warfare." NTA 1.5.2.3 is the lowest level of the "NTA 1 Deploy/Conduct Maneuver" hierarchy with sister tasks of

"NTA 1.5.2.1: Conduct Surface Warfare" and "NTA 1.5.2.2 Conduct Air Superiority Warfare." Each task is given a short description describing the specific aspects of the task. For "Conduct Undersea/Antisubmarine Warfare" the description is:

> To establish and maintain supremacy in assigned operating area through employment of assets to ensure freedom of action of friendly maritime forces in face of undersea threats such as submarines, mines, and underwater swimmers. (Department of the Navy, 2001)

The UNTL adds to the tasks various measures of performance. Some tasks have only a few suggested measures and others are more extensive. The 22 suggested measures for the "Conduct Undersea/Antisubmarine Warfare" task are shown in Table 12.

Table 12. UNTL tactical level task measures for NTA 1.5.2.3 Conduct Undersea/Antisubmarine Warfare (From: Department of the Navy, 2001)

M1	Percent	Of assigned targets destroyed
M2	Percent	Of assigned targets cannot continue assigned mission
M3	Number	Of assigned targets launch weapons after engagement
M4	Number	Of assets available to prosecute subsurface threats
M5	Percent	Acoustic coverage while in torpedo danger zone
M6	Percent	Correct probable submarine classification
M7	Percent	Correct certain submarine classification
M8	Time	To search designated area
M9	Time	Required to communicate with friendly submarine
M10	Percent	Of successful communications attempts with friendly submarine
M11	Percent	Of Blue-on-Blue/Grey/White engagements
M12	Time	Of asset response time from classification of probable submarine until ASW platform on scene
M13	Percent	Radar flooding within LLOA during transit/in Vital Area
M14	Percent	Radar flooding within ASW CIEA
M15	Percent	Radar flooding within torpedo danger zone
M16	Percent	Probable submarine (or higher) contact engaged or negated prior to torpedo danger zone
M17	Percent	Probable submarine (or higher) contact within torpedo danger zone engaged or negated prior to attack
M18	Number	Friendly ships sunk or damaged
M19	Number	Attacks against non-submarine contacts
M20	Minutes	SCC/SSN time to complete tactical communications
M21	Y/N	BELLRINGER conducted via all available means
M22	Minutes	From BELLRINGER to communications established

The creation of the UNTL has ensured the Navy is on the right track when it comes to the determining the tasks stage of system development. Future success with task definitions will only be guaranteed when the UNTL and UJTL are utilized during the systems engineering development process.

c. Creating Functions

Once the tasks are identified, the next step in system development is the definition of functions. There are various generic functional lists (similar to the UNTL for tasks) or functions can be derived from scratch. The purpose of the functional analysis is to define the low level activities, in the form of verbs, performed by the system. These functions are created in a hierarchical format and then displayed in the form of a functional hierarchy, functional flow block diagrams (FFBD), enhanced functional flow block diagram (EFFBD), matrix (N2) diagram, and/or an Integration Definition for Function Modeling (IDEF0) diagram.

Similar to the UUVs being developed by the Navy, a project at the Naval Postgraduate School entitled Tracking of Underwater Narco-subs using Autonomous Submersibles (TUNAS) created a functional analysis of a UUV for the interdiction of semi-submersible drug submarines in the United States Southern Command region (Brocht, Layne, Matson, McMurtrie, Schindler, & Vandenberg, 2009). Though the mission of the system changes from a submarine deployed UUV, the high level functions are analogous. From a high level, shown in Figure 26, the EFFBD broke down six high level functions. A FFBD would look similar, but would not show the triggers, inputs, and outputs linking the functions.

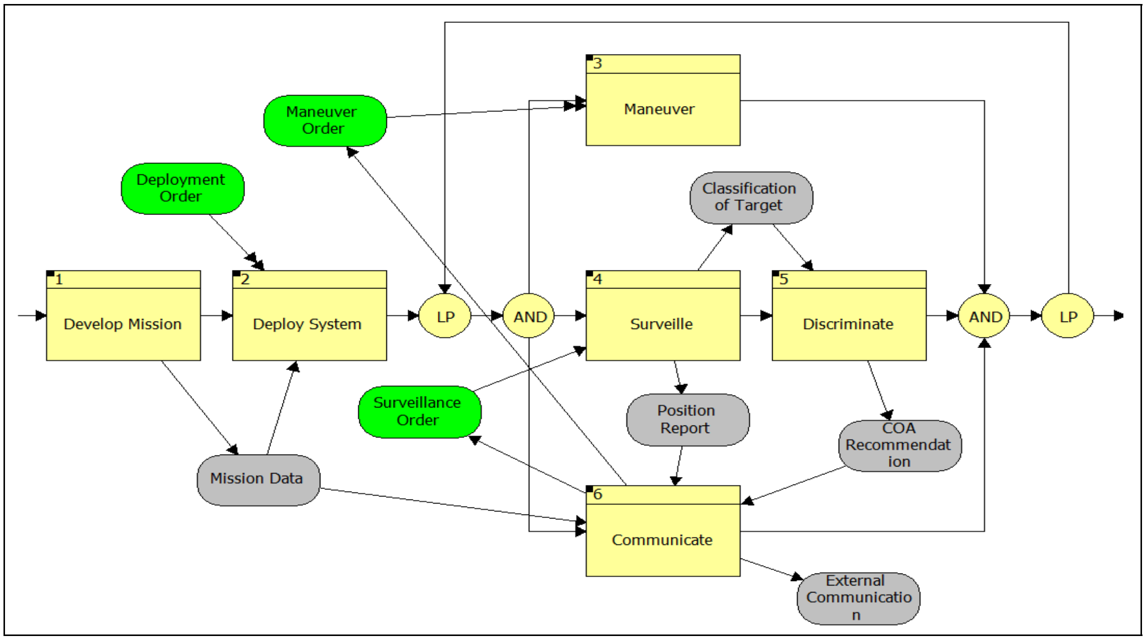

Figure 26. High level EFFBD for TUNAS sample UUV system (From: Brocht, Layne, Matson, McMurtrie, Schindler, & Vandenberg, 2009)

An N2 matrix diagram for high level of TUNAS displays the same information as the EFFBD, but in a different manner. Instead of showing flow between the functions and sequential order, it aligns the functions diagonally through the diagram and shows the input and output objects along the horizontal axes. The directions of the arrows indicate the sequence in which data flows between the functions. TUNAS N2 matrix diagram is shown in Figure 27.

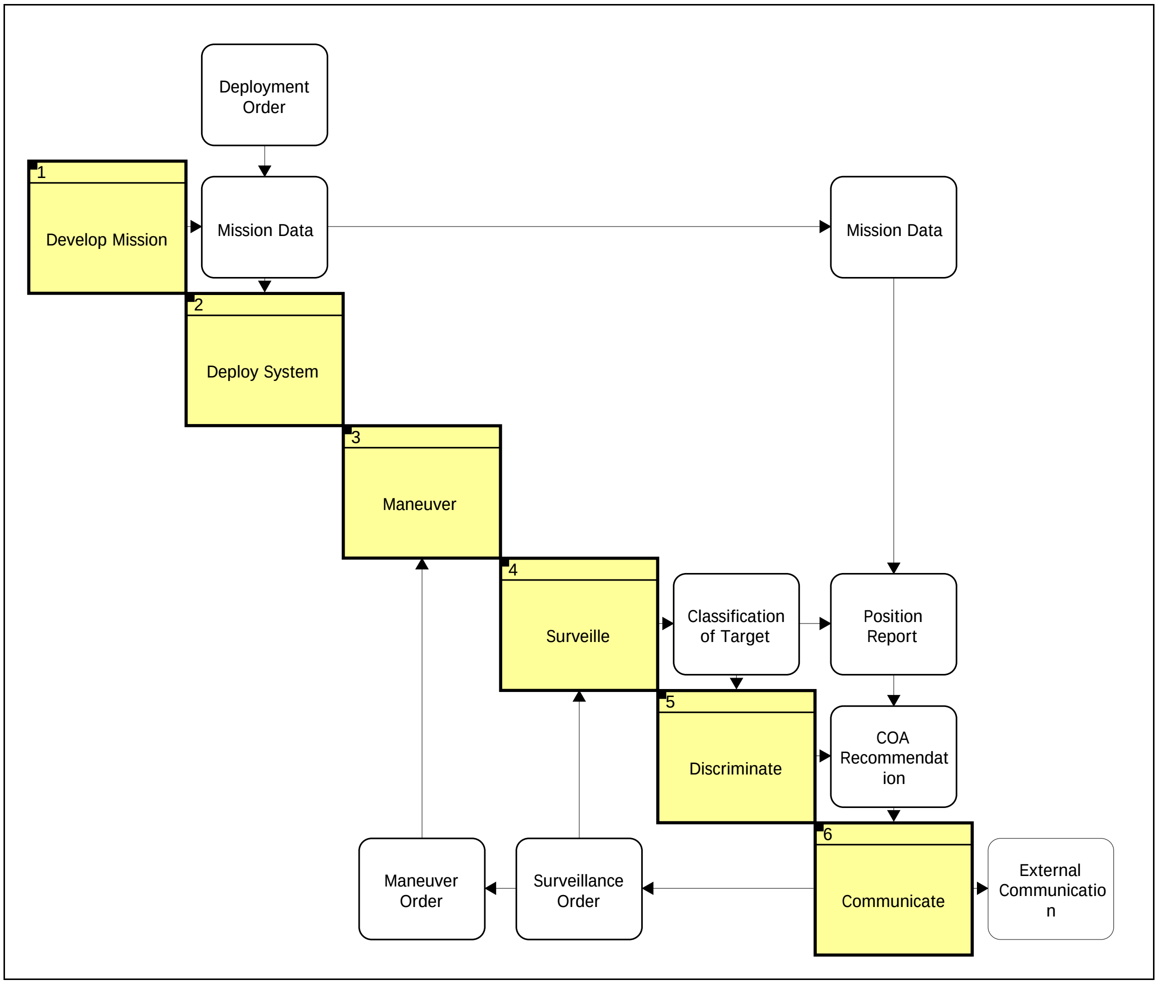

Figure 27. N2 matrix diagram for TUNAS sample UUV system (From: Brocht, Layne, Matson, McMurtrie, Schindler, & Vandenberg, 2009)

N2 diagrams and EFFBDs/FFBDs show the same information presented in different manners. The use of both of these is often considered redundant. An IDEF0 diagram, on the other hand, shows a unique perspective on the functional analysis. The purpose of an IDEF0 is to establish system boundaries and identify interfaces and bind the problem statement. In addition to the inputs and outputs shown above, IDEF0 diagrams include controls and mechanisms for each function. IDEF0 diagrams follow a Input-Control-Output-Mechanism sequence illustrated in Figure 28.

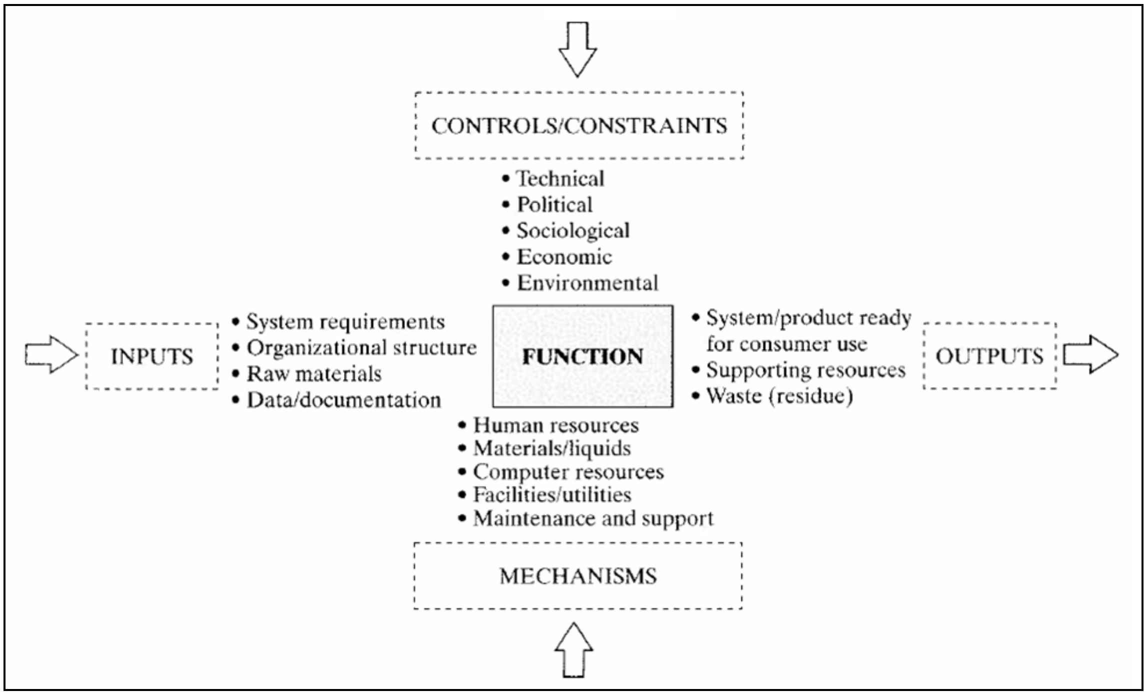

Figure 28. IDEF0 diagram template (From: Blanchard & Fabrycky, 2006)

Past programs have done a poor job of functional analysis, but formal training of systems engineers has led to current and future Navy programs doing a reasonable job with these stages of the system design process. The downfall of the current program is documentation of sources for future program use. Future UUV systems must continue down the path of proper functional analysis, properly documenting this analysis in order to enable the collaboration of that information with future sister programs.

d. Designing Components

The most successful stage of system design for the DoD is the component design phase, and this success can be attributed to the amount of experience the DoD has during the stage. Unfortunately, when components are assigned to systems without set missions, requirements, tasks, and functions this stage may produce components that achieve seemingly triumphant results but do not do what the stakeholders need. Additionally, systems are being overdesigned by including components that perform

functions for tasks that are not necessary or do not exist. Current UUV projects in development are stuck at the component design phase without the benefit of the other stages of systems engineering.

The future solution comes in the form of model-based systems engineering (MBSE) and product lifecycle management (PLM) software. MBSE, similar to the four stages of system design described in this section, creates traceability amongst components, functions, and tasks. With proper MBSE, if the system developers determine a task is not necessary and it is deleted then associated functions and components will be flagged for review. This feature can bring about drastic cost reductions from "over-engineering" a system from the component level. Similarly, PLM software starts at the component level and focuses on the lifecycle of a product from cradle to grave. This is a good way to determine the LCC of a program and predict the manufacturing, logistics support, and transportation costs that are often hidden in the design phases. With proper systems engineering and the use of MBSE and PLM software, the Navy is on the right track for component design, and should apply these concepts to future submarine UUV programs.

2. Feedback

Feedback should not only be gathered internally to the system, but must be used from similar programs to gather valuable data necessary to maximize the probability of successfully engineering a new complex system. The first three submarine UUV programs discussed in Chapter III (NMRS, LMRS, and MRUUV) failed in gaining proper inter-program feedback. Though these programs have been unsuccessful in their goal of creating a successful UUV system for use by the Navy, there have been valuable lessons learned from the programs that can be applied to future systems. Unfortunately, these valuable lessons have not been properly assessed and applied to other programs through the correct feedback chains. In the past, the Navy did not have a common program office for communicating data and feedback amongst systems. This lack of feedback has caused programs, with clearly stated requirements, to develop to a certain level (the amount of development of each system has been different) and then become

cancelled by the Navy only to start a new program from the beginning. Ideally, it is not only important that a program has requirements, but it will also need to take lessons learned from previous similar programs.

3. Trade Studies

The systems design process is an iterative process, allowing programs to flourish with the right amount of feedback. Adding to these iterations are series of trade studies, similar to the system complexity trade study discussed in Chapter II, which will determine the optimal system design while varying the amount and types of inputs. Trade studies are performed to (Tauras, 1995):

- Support functional analyses and allocation of performance requirements and design constraints,
- Define a preferred set of performance requirements satisfying identified functional interfaces,
- Determine performance requirements for lower level functions when higher-level performance and functional requirements cannot be readily resolved to the lower-level, and
- Evaluate alternative functional architectures.

There is not a common standard for the performance of a trade study; one approach taught by the DAU and implemented by the DoD is outlined in Figure 29.

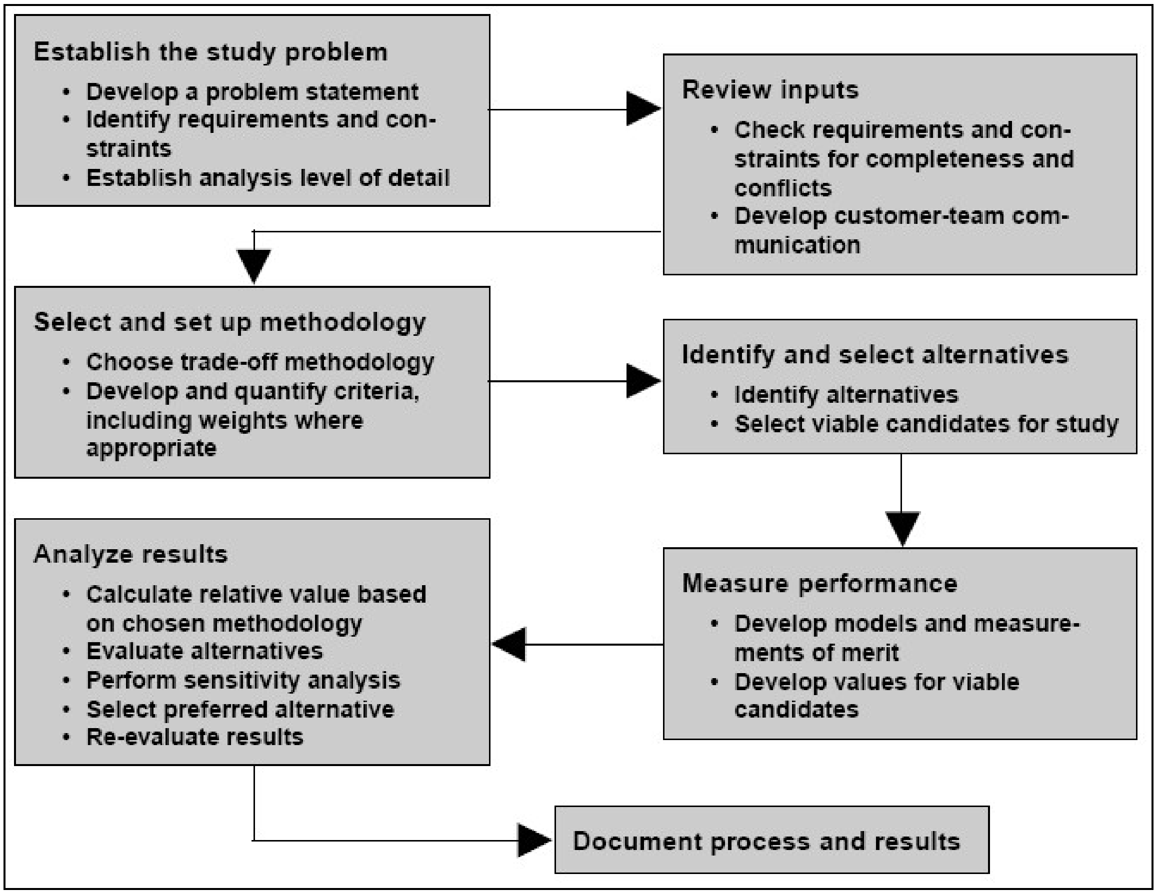

Figure 29. Trade study process (From: Defense Acquisition University, 2001)

It is beyond the scope of this thesis to go into specific trade studies that a UUV program will perform, but it is important to understand that that all suggestions made throughout this thesis must be considered as only inputs (or are the result of outputs) to a formal trade study.

C. MANNING AND MAINTAINABILITY ANALYSIS

Another approach to systems engineering is given by Benjamin S. Blanchard and Wolter J. Fabrycky in their textbook titled Systems Engineering and Analysis, and shown in Figure 30. In this text, the authors describe systems engineering as a lifecycle and point out the interactions that take place amongst activities in the lifecycle. In the lifecycle, there are distinct stages of design, shown in Figure 30. These incremental stages allow for the inter-stage feedback to provide real time response and allows for flexibility in the growth of the design process. Included in this figure, but not discussed

in the previous analysis, are the following stages: 1) production and/or construction, 2) utilization and support, and 3) phase-out and disposal. The addition of these phases in the systems engineering process allows for manning and maintainability aspects of the developed systems to take part in the early developmental stages.

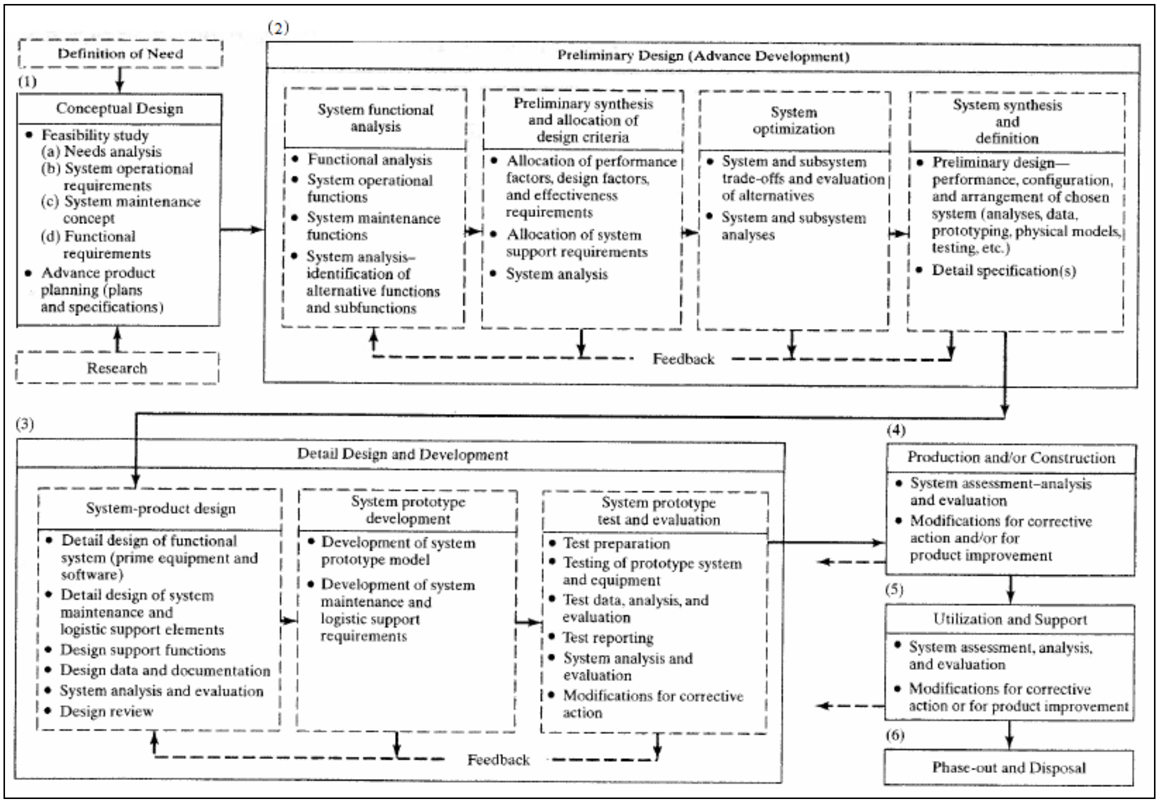

Figure 30. Systems engineering lifecycle (From: Blanchard & Fabrycky, 2006)

1. Manning Analysis

Future submarine UUV systems should account for manning during the developmental stages of the systems engineering lifecycle. A 2010 study by the Congressional Budget Office determined that O&S costs make up 49% - 56% of the LCC for four analyzed Navy ships (MCM-1, FFG-7, DDG-51 Flight IIA, and CG-47). The study showed that the smaller the vessel, the higher proportion personnel costs allocated in the budget. In the case of the MCM-1 and DDG-51 Flight IIA, personnel costs represented up to 38% and 29%, respectively, of total LCC, and procurement costs accounted for less than 50% of the LCC in all cases (Elmendorf, 2010). Even with this

balance, procurement costs overshadow manning costs in the average decision during the DoD acquisition process. As the defense budget begins to shrink, it is imperative that future systems focus more on LCC than acquisition costs.

a. Logistics Support Elements

Manning is not always taken specifically into account when doing the front-end design of a system, but operations and logistics support elements are. Table 13 outlines the specific applications in which logistics support, including manning considerations, should be considered during the lifecycle for the Blanchard and Fabrycky systems engineering model. This approach is augmented by "UAV Lesson 5" which states that programs should consider supportability up front, including in the conceptual design phase.

Table 13. Summary of logistics support elements in the systems engineering lifecycle (After: Blanchard & Fabrycky, 2006)

Stage	**Application of Logistics Support**
Conceptual Design	Quantitative and qualitative supportability requirements for the system.
Preliminary Design	Allocation of quantitative and qualitative supportability requirements. Preliminary supportability analysis, formal design review.
Detail Design and Development	Design support, supportability analysis, provisions and acquisition of logistic support elements, test and evaluation of logistics support capability, formal design review.
Production / Construction	Acquisition of logistic support elements; test and evaluation of logistics support capability; data collection, analysis, and corrective action.
System Utilization and Lifecycle Support	Re-provisioning and acquisition of logistic support elements; data collection, analysis, and corrective action; system / product modification (as required).

b. Use of a Dedicated Cadre

Current submarine related UUVs in use by the Navy have a specific cadre of operators that will deploy with the systems. While deployed, the cadre, part of the

Submarine Development Squadron (DEVRON) 5 UUV Detachment, will operate and maintain the UUVs with limited help of ship's force. The continued use of dedicated personnel working out of the same office adheres to "UAV Lesson 3" and structures a process for sharing data between various UUV systems. Top Navy experts feel that future UUV systems will continue to utilize the cadre detachment system until UUVs become a completely integrated part of the submarine and are operated as a weapon or off-board sensor, like a torpedo or towed array.

Future programs will see an immediate spike in manning due to the operators, contractors, and intelligence specialists needed, but this spike will eventually level off when contractors are no longer necessary to complete maintenance, intelligence specialists are not needed for every mission, and ship's force eventually becomes solely the operators and maintainers of the UUVs. Due to the use of a cadre, and not only ship's force, the Navy must change its initial point of view of using UUVs for reducing manning to one of increasing capability. The reduction of manning, if at all feasible, is a long-term goal of unmanned systems, but should not be thought of as an immediate benefit.

c. Operator Ratings and Navy Enlisted Classification Codes

A professionally trained cadre of individuals does bring some immediate benefits to the system design, development, and deployment. First, as discussed with "UGV Lesson 4," maintenance can be done at the user level. Because the cadre works with the same UUVs and are not attached to the host platform, they come with experience in both the operating and maintaining aspects of the systems. Additionally, new Navy enlisted classification (NEC) code for UUV operators, 9550, ensures future enlisted operators will continue to receive specialized training for the operation and maintenance of UUV systems.

The source ratings are limited to submarine qualified personnel of rates are 1) Electronics Technician (ET), 2) Sonar Technician Subsurface (STS), 3) Fire Control Technician (FT), and 4) Machinist's Mate (MM). Because the ratings are limited to submarine qualified personnel, the Navy can ensure that the operators will have

operational experience and UUV expertise. As UUVs move away from the use of detachments for operation and maintenance, the same ratings will be available as part of ship's force and this will guarantee the same quality level of users as provided by the cadre. Training of ship's force in the operation and maintenance routines would be a long-term goal and is not something that is currently being considered top priority.

9550 Unmanned Undersea Vehicle (UUV) Operator

Performs duties as a member of a Submarine Launched UUV Detachment. Operate and perform organizational level maintenance on all rating oriented equipment aboard UUV's and support equipment.

Source Rating: ET, STS, FT, MM	Billet Paygrades: E5-E8	Personnel Paygrades: E5-E9
Course: Mandatory	CIN:	CDP:
Sequence Code: 4		NR Ind: N
Component NEC:	Related NEC:	Open to Women: No
Primary Advisor: CNO N871B	Technical Advisor: NAVSEA 05	ECM: BUPERS 323

Figure 31. Navy enlisted classification code 9550 description (From: Bureau of Naval Personnel, 2010)

When current 9550 NEC codes report to the DEVRON 5 UUV Detachment, they receive mainly "on-the-job" training augmented by technical manuals reading, computer-based training, and department-wide training. All UUV operators follow the same qualification process, as the skill sets used by the operators are independent of their source rating. Once qualified, the operators deploy with the UUV systems and work 12-hour shifts during their deployments, lasting an average of two weeks each. Additionally, the operators spend 1-2 months training and planning prior to each deployment.

The size of the deployed cadre varies depending on the system being operated, but a general manning model would include one supervisor with at least one or two operators per shift, giving a minimum of three operators per deployment. The leadership of these cadres is currently a mix of Warrant Officers and Limited Duty Officers (LDOs), and this will most likely not change for cadres of the future.

2. Maintainability Analysis

Maintainability is an important aspect of the system lifecycle to consider early as it will effect the quantitative and qualitative requirements (such as MTBF and

availability) as well as the manning and logistic supply requirements. Table 14 summarizes the elements of maintainability as they apply to the systems engineering lifecycle introduced by Blanchard and Fabrycky. As with "UAV Lesson 2," this method supports the importance of acquiring maintainability data throughout all stages of system development.

Table 14. Summary of the role of maintainability in the systems engineering lifecycle (After: Blanchard & Fabrycky, 2006)

Stage	**Application of Maintainability**
Conceptual Design	Maintenance concept, quantitative and qualitative maintainability requirements for system, maintainability planning.
Preliminary Design	Allocation of maintainability requirements, maintainability analysis and trade-offs, maintenance engineering analysis, design support, maintainability predictions, formal design review and approval.
Detail Design and Development	Maintainability analysis and trade-offs, maintenance engineering analysis, design support, maintainability predictions, maintainability demonstration, formal design review and approval.
Production / Construction	Maintainability test and evaluation; maintainability data collection, analysis, and corrective action.
System Utilization and Lifecycle Support	Maintainability data collection, analysis, and evaluation; system modification (as required).

a. Organizational, Intermediate, and Depot Level Maintenance

DoD systems operate with three levels of maintenance: organizational, intermediate, and depot, described in Figure 32. A successful maintenance plan should incorporate all three levels of support. The manning analysis discussed how the use of a dedicated cadre of operators supported the ability to perform organizational level maintenance. The cadre will also support intermediate level maintenance, as it could be performed on board a support vessel, pier-side, or at the UUV detachment headquarters.

For UUVs, depot level maintenance will most likely be performed by the contractor only, easing some of the logistics support burden of the Navy when it comes to the most complex levels of repair.

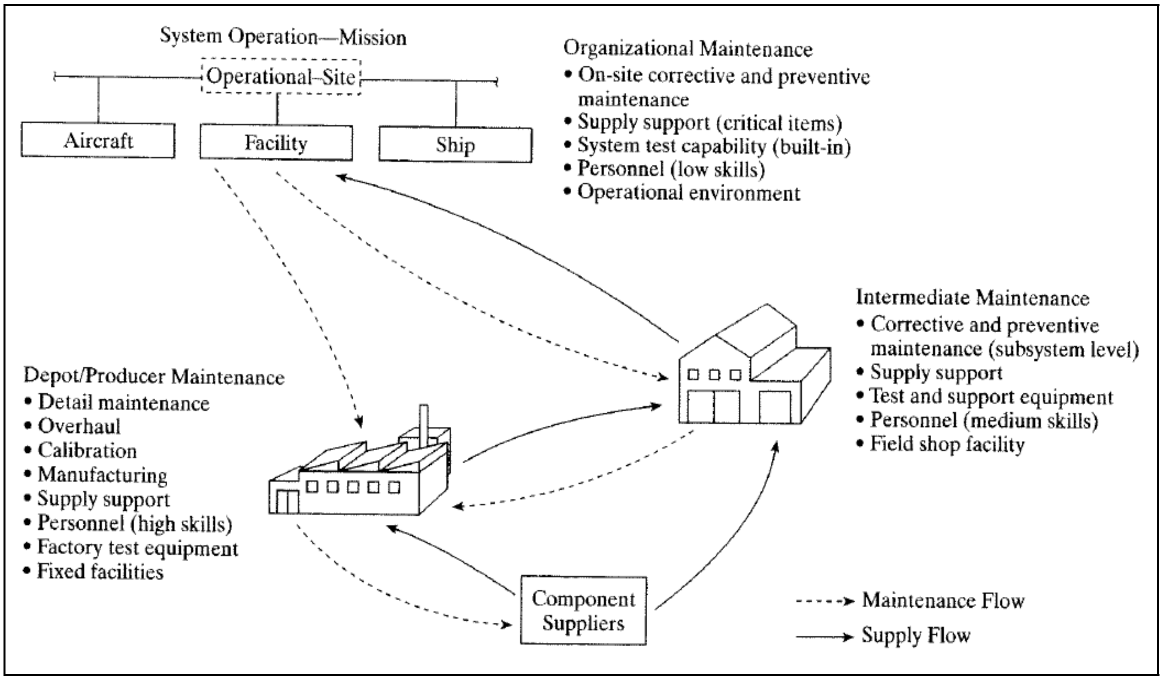

Figure 32. System operational and maintenance flow (From: Blanchard & Fabrycky, 2006)

The organizational, intermediate, and depot level concepts are then broken into specific criteria in Table 15.

Table 15. Criteria for organizational, intermediate, and depot levels of maintenance (From: Blanchard & Fabrycky, 2006)

Criteria	Organizational Maintenance	Intermediate Maintenance		Supplier/Manufacturer/Depot Maintenance
Done where?	At the operational site or wherever the prime elements of the system are located	Mobile or semimobile units	Fixed units	Supplier/manufacturer/depot facility
		Truck, van, portable shelter, or equivalent	Fixed field shop	Specialized repair activity or manufacturer's plant
Done by whom?	System/equipment operating personnel (low maintenance skills)	Personnel assigned to mobile, semimobile, or fixed units (intermediate maintenance skills)		Depot facility personnel or manufacturer's production personnel (high maintenance skills)
On whose equipment?	Using organization's equipment	Equipment owned by using organization		
Type of work accomplished?	Visual inspection Operational checkout Minor servicing External adjustments Removal and replacement of some components	Detailed inspection and system checkout Major servicing Major equipment repair and modifications Complicated adjustments Limited calibration Overload from organizational level of maintenance		Complicated factory adjustments Complex equipments repairs and modifications Overhaul and rebuild Detailed calibration Supply support Overload from intermediate level of maintenance

b. Sample Organizational Level Maintenance Routines on UUVs

An estimate for future maintenance routines for the Navy can be taken from current industry vehicles. The HUGIN 1000 AUV is a smaller, militarized version of the previously discussed HUGIN 3000 that is part of a North Atlantic Treaty Organization MCM Group. The HUGIN 1000 has operator level maintenance consisting of visual inspections and component flushing, and the amount of time dedicated to routine organizational level maintenance is shown in Table 16. Short maintenance times on board a submarine are ideal as manning, space, and time are all limiting factors when compared to traditional industrial launch and recovery platforms. Fortunately for comparison to future Navy UUVs, down time in industry means loss of revenue and therefore man-hour maintenance times have been optimized to short intervals.

Table 16. Organizational level man-hour requirements for the HUGIN 1000 AUV (From: C. Hancock, personal communications, April 5, 2010)

Maintenance Interval	**Man-hours**
Before each dive	2 men, 0.5 hours each
After each dive	2 men, 1.0 hours each
Every 50 hours of power-on time	2 men, 2.0 hours each
Every 500 hours of power-on time, or 3rd month	2 men, 3.0 hours each

It is expected that military use of UUVs on board submarines will have a slightly different maintenance schedule, as the long term interval maintenance (50 hour and 500 hour) may be done at the intermediate level. Pre- and post- deployment maintenance routines, however, should follow very closely to HUGIN 1000. Maintenance done at the user level will not only require basic skill sets, but limited space and supplies as well. The space and supply limitation will be even more restricted on board a submarine. The post mission degree of maintenance performed on a HUGIN 1000 is on par with the type of maintenance that could be performed after UUV recovery on a submarine, as shown in Table 17. The events shown in the table can be completed simultaneously, ultimately reducing the length of time spent on maintenance. The simultaneous completion of the jobs, however, would require an increase in the manning necessary to complete the jobs. The reliability data collected by the HUGIN 1000 AUV to determine the maintenance intervals was collected during all stages of the systems lifecycle, as suggested by “UAV Lesson 2.”

Table 17. Organizational level maintenance performed on the HUGIN 1000 AUV after each mission (From: C. Hancock, personal communications, April 5, 2010)

No	Sub-System	Maintenance Routine	Time
1	Vehicle Hull	– Clean and inspect – Inspect shells, vehicle units, and mechanical parts	20 min
2	Propulsion Motor	– Inspect oil buffer	2 min
3	Rudder Section	– Inspect oil buffer for leakage	2 min
4	Air Recovery Bladder	– Inspect for damages	2 min
5	Drop Weight	– Inspect release mechanism	5 min
6	Flashing Light	– Clean exterior with fresh water	2 min
7	Mission Start Key	– Clean exterior with fresh water	2 min
8	Control Container	– Rinse container	4 min
9	Battery System	– Refill oil in buffer	10 min
10	Payload Container	– Rinse container	4 min
11	Transponder for HiPAP	– Rinse Container	2 min
12	MST Transponder	– Rinse Container	2 min
13	Transducers and Containers	– Perform insulation test	10 min
14	Recovery System	– Flush with fresh water – Test release and reset alarm – Check and grease the o-rings – Inspect for leakage	10 min
15	Recovery Bladder	– Inspect for leakage and visible damage	5 min
16	Drop Weight	– Flush the drop weight mechanism	2 min
		Total maintenance time:	***84 min***

c. *Future Maintenance Ideas for Large-Scale UUVs*

One problem with the Navy's 2004 UUV Master Plan definition of a Large Vehicle is that it places all UUVs with a diameter greater than 21 inches into a generic category (Department of the Navy, 2004). Some UUVs, larger than 21 inches, like the Sea Stalker at 38 inches, have the ability to be housed in a DDS on board a SSN or SSGN, while other UUVS, like the Sea Maverick at 48 inches, do not have the ability to be accommodated in a DDS. Additionally, when even larger UUVs are militarized, in some cases up to 80 inches, they still fit in the generic Large Vehicle class. This poses a problem for the current UUV operators and maintainers as they are given vehicles with a

high variance in capabilities that must be treated in the same fashion. For the case of this discussion, an extra class "Very Large Vehicle" should be added to include vehicles that are larger than those that can be accommodated in a DDS.

As the UUVs become larger, as is the case of the Very Large Vehicle, submarines cannot be used to perform organizational level maintenance. Additionally, as the UUVs become more complex the personnel may not be properly trained in performing the maintenance activities or the supplies may not be available to the operators, therefore causing the submarine to be an inadequate location to perform the organizational level maintenance. As a result, UUVs may need to incorporate some type of support vessel to couple with to perform routine preventative and corrective maintenance. With the small amount of submarine tenders in the Navy, UUV maintenance cannot be imposed on the crews of the USS Emory S. Land (AS-39) or USS Frank Cable (AS-40). The more likely answer to which vessel to use is LCS, due to various features of the vessel that lend to UUV support, including:

- Off-board vehicle launch and recovery system
- Large mission bay
- Mission bay lift
- Mission module packages

Contrary to some belief, the use of LCS for UUV launch, recovery, and logistic support does not remove the need for a submarine to be involved in the loop. The submarine aspect of LCS-submarine tandem can be used for covert launch of the UUV (later to be recovered by LCS), undersea communications, and mission updates. A sample CONOPS involving a SSN and LCS is covered in the next section.

d. Power Concerns and Options

One of the greatest concerns of the Navy with UUVs is power. Currently, batteries are the source of power and will be until a better method can be developed for undersea use. A complication in 2008 with the Advanced SEAL Delivery System catching fire during a lithium ion battery charge has added additional constraints on the

types of batteries approved. The Navy has not authorized the use of lithium battery technology onboard a SSN, which include systems housed in the DDS. Most UUVs operated by industry, however, are successfully using lithium battery technology as their power source and are noticing endurances that are up to an order of magnitude longer than that of alkaline batteries.

The type of power source chosen for the future deployable UUVs will have a drastic impact on the level of maintenance necessary at the organizational level. Currently, the average UUV concept considers a rechargeable battery (lithium or other) for a power source, but this should not be the only form chosen. Even if the requirements focus on the use of batteries as a constraint, it is important to do a trade-off between primary (single-use) and rechargeable batteries. Although the use of primary battery technology will generally require a battery replacement at the intermediate or depot level after each use, versus a simple recharge at the organizational level, some primary battery UUVs have shown an endurance of nearly three times that of their rechargeable counterparts of the same weight and volume (J. Bellingham, personal communications, April 29, 2010). The added capability of the tripled endurance may be an acceptable trade-off, especially when dealing with UUVs that are attached to submarines that have limited deployment lengths. As discussed with "UAV Lesson 6," the longer the endurance, the greater the MTBM, and the less manning and logistics support necessary to support the program.

D. CHAPTER SUMMARY

This section discussed the systems engineering process and went into detail on two parts of the systems engineering lifecycle, manning and maintainability, as they apply to a future UUV program. It is important that stakeholders fully understand the systems engineering process if they want to make a successful submarine UUV program, similar to those discussed in the next chapter.

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VI. SAMPLE CONCEPTS OF OPERATIONS

A. INTRODUCTION

To move forward in the development process, it needs to be understood that there is not one "cookie cutter" CONOPS that can apply to all submarine UUV programs. This section includes two different CONOPS that employ technologies that are reasonably mature today. The Navy should analyze these suggestions as possible programs of record. These CONOPS will focus mainly on the impact the programs will have on the manning and maintainability aspects of the submarine force. These CONOPS are limited in scope to discuss the items presented in the beginning of the chapter and were created using a combination of published Navy ideas, literature research, and personal interviews. They are not intended to consider all aspects of the UUVs operations. Both of the CONOPS are set in the near future (less than 10 years) and assume only little technological advances have been made to overcome some of the barriers in place today. Lastly, the two CONOPS can be completed without changing the current deployment schedules of the submarines, as the missions being completed are similar to time and scope to current submarine missions.

B. GROUP OF SUBMARINE-LAUNCHED UUVS

1. Operational Situation

While operating near enemy waters, the latest Virginia-class SSN is equipped with six 21-inch UUVs, similar in size and functionality to the ASM-X (see Chapter II). The crew of the Virginia class submarine has been given orders to gather short-range, encrypted communication data near the coast of an unfriendly nation. This data is essential to the mission of a CSG operating in the region and therefore must be captured in near real-time, decrypted, and relayed from the SSN to the CSG commander. The littoral nature of the coastline near the nation has made the area inaccessible to the submarine.

It is the decision of the commanding officer to utilize four of his available UUVs and begins to deploy them toward the AOI. Each UUV is programmed with critical

mission data and sequentially shot from one predetermined torpedo tube. Each UUV will navigate along a programmed path to a specified point of interest, all while autonomously avoiding previously unidentified obstacles that may get in its way. The first UUV will arrive near the communications tower and the other three UUVs will set up as communication nodes between the first UUV and the Virginia-class submarine, as shown in Figure 33. The data will be decrypted and analyzed in near real-time on board the SSN by intelligence personnel and then relayed to the CSG commander. After the commanding officer has determined that no more data will need to be collected, an order is sent to the four deployed UUVs via ACOMMS (unless a better form of technology can be proven) and they return to rendezvous with the SSN.

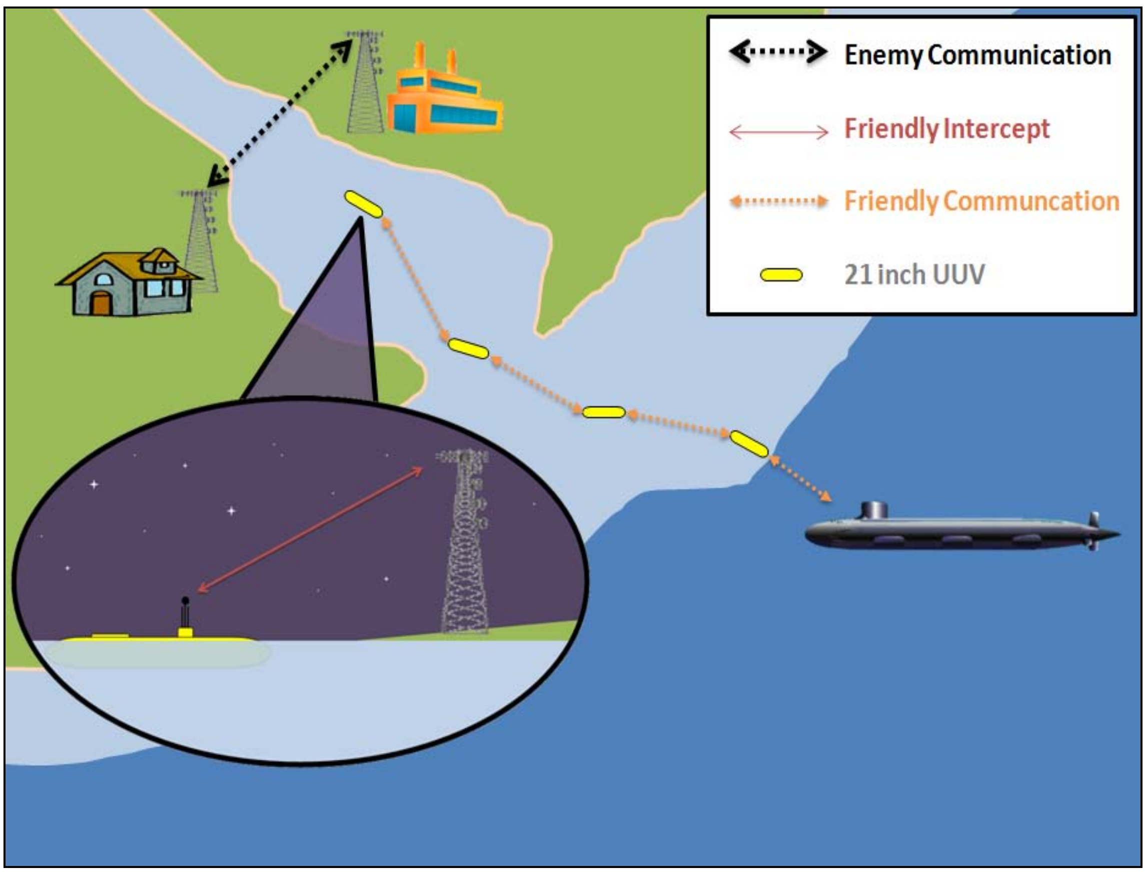

Figure 33. High level graphical depiction of operational situation for a group of small submarine-launched UUVs

2. Payloads

The preference of the Navy is a fully mission configurable UUV with modular payloads. This concept will provide both cost savings and mission flexibility in the long term, but is not something that will be successful for a UUV of the near future. Instead, a clearly defined mission, as shown above, will lead to specific UUV designs that will be in place on submarines. To complete a vital ISR mission, the systems will be outfitted with a retractable antenna that is extended to collect the encrypted, short-range communications when the vessel breaches the surface, similar to the antennas used in the Sea Stalker UUV.

The torpedo room on board a Virginia-class submarine was not initially designed to launch or recover UUVs and some adjustments have been made in order to support the new systems. Originally equipped to carry 26 tube-launched weapons, the addition of the UUVs reduce the weapon load to 18 (6 spaces filled by UUVs and 2 by support equipment). Unlike the LMRS program, the UUVs have been designed to be launched and recovered in the same tube, allowing for weapons loading in 3 of the 4 available tubes. Because the use of UUVs decreases the original capability of the weapon systems and is thought of as an extreme detriment by some of the war-fighters, only one Virginia-class submarine is outfitted with torpedo tube launched UUVs.

The short-term cost savings will be implemented by varying the types of systems that will be loaded on board the Virginia-class submarine. As an example, only two of the six UUVs will be outfitted with the retractable antenna system and the other four will only act as communication nodes, not gather the ISR data. The communication amongst the UUV nodes and eventually to the SSN is done using ACOMMS (or other) technology with which all six UUVs is equipped. The supply of six UUVs would be able to perform a maximum of four missions – two missions per UUV group and only two ISR gathering UUVs. The amount of communication node UUVs would depend on the specific operational situation.

A challenge faced by the utilization of the forward end of a Virginia-class submarine to house UUVs is the lack of electrical-power distribution systems needed to

recharge the system's batteries (Button, Kamp, Curtin, & Dryden, 2009). Taking this and endurance into consideration, the UUVs discussed in this scenario are designed with primary batteries. Although the application of single-use batteries will limit the UUVs to only one or two missions per deployment, it has several advantages, including:

- **More endurance.** Primary batteries have up to three times the endurance of secondary batteries. This means that a UUV designed to operate for only one mission can spend more time on station and carry out more tasks than its rechargeable equivalent.
- **Less supportability.** There is no need for complex electrical-power distribution systems on board the SSN to recharge the batteries. Additionally, there will be a need for fewer spare parts that will have to be stored in the torpedo room.
- **Less operational level maintenance.** Systems will not need the operator to charge the system, monitor the battery, or perform any upkeep on the battery that would typically be done with a rechargeable system. Because the systems will need to be brought back to an intermediate level facility for battery replacement, there will be little to no operator maintenance performed after the battery has been depleted.

Due to restrictions on board submarines, the primary batteries used will not take advantage of lithium technology. This restriction will limit the average useful mission length to 12-18 hours, a range of 12-15 nautical miles, and a top speed less than 5 knots. Though this is far shorter than the 30-day ISR mission desired by the Navy, there are several missions (similar to the one described above) that will benefit from a short range UUV. Additionally, the ability to launch and recover from a submerged SSN will shorten the needed ferry range and allow for more time on target.

The technologies available and mission specifics may drive the communication range between the UUV nodes. To ensure successful communication amongst UUVs, it may be necessary to use additional leave behind (or recoverable) communication nodes, similar to those described in the Seaweb concept (Rice, 2005) and shown in Figure 11.

3. Maintenance

As mentioned earlier, very little organizational level maintenance will need to be performed on the systems. After each deployment, the systems will need to be cleaned to ensure that they do not deteriorate prior to the intermediate or depot level maintenance phase. Additionally, if the UUVs are used on a second mission, a maintenance routine similar (minus the battery upkeep) to that of the HUGIN 1000 vessel (shown in Table 17) will need to be completed. The remainder of the maintenance executed will be on the support systems. A majority of the focus will be on the launch/recovery system and communication.

Even though the payloads are considered simple, the use of the UUVs for a maximum of two deployments will allow the maintenance routines to be more complex and require less time, thus allowing for proven systems with a lower operational availability (A_o), as described in the equation below, in relation with MTBM and mean down time (MDT). A lower A_o is generally considered to be a deterrent in the decision making process. In this case, however, the higher MDT does not negatively affect the mission and would lower the support costs of the system. This tradeoff could be the determining factor for the the stakeholders.

$$A_o = \frac{MTBM}{MTBM + MDT \uparrow} \rightarrow A_o \downarrow$$

4. Manning

Sailors aboard the Virginia-class submarine will not be properly trained to operate and perform the maintenance necessary, requiring the use of a cadre of personnel to assist the crew. This cadre, most likely from the DEVRON 5 UUV Detachment, would consist of a supervisor and up to four sailors. The supervisor would be at a minimum rank of Chief (E-7), but could be a Warrant Officer or junior (O-3 or below) LDO. The sophisticated nature of the launch/recovery system and the communications would most likely require the use of contractors to aid in the organizational level maintenance. In this

case, two contractors may be necessary (one for each system), but they would be able to replace the members of the detachment. As the detachment becomes more proficient with using the equipment, these contractors can be replaced by detachment personnel. A summary of the crew necessary to support this mission is shown in Table 18. Lastly, the nature of the ISR missions performed by the UUVs may also require specific intelligence personnel to augment the crew. This is currently a typical practice on board submarines and is not shown in the summary table.

Table 18. Summary of manning requirements necessary to support a group of submarine-launched UUVs

Job Title (Quantity)	**Description**
\Supervisor (1)	– In charge of UUV detachment and interfaces with ship's crew – Minimum rank of E-7 – Stands watch and performs maintenance, as needed
Operator / Maintainer (2)	– Work in shifts while UUV is deployed – Perform organizational level maintenance – Rank of E-4 through E-6 – Mixture of submarine qualified rates (ET, STS, FT, MM)
Contractor (2)	– Perform maintenance on support equipment – Long term goal would be to replace with detachment

5. Recommendations

In order to develop a successful UUV program, it will need to begin with a specific mission or set of missions. A mission configurable, multi-mission, sophisticated UUV has great uses in the long-term future, but this should not be the short-term focus of a Navy program. In the case of the group of small submarine-launched UUVs, a single mission (or small set of similar missions) should be the desired intent of the Navy. An initial trade study may show that the amount of personnel necessary to support this type of mission is not worth the small benefit of a single mission, short endurance UUV program. With time, the contractors will be replaced by detachment personnel, and the detachments will be replaced by ship's force. Eventual advances in technology will

allow for longer endurance and more sophistication. Though the financial facts may look discouraging, a program similar to this is necessary to advance the UUV technology.

To counteract the relatively high cost of manning, the UUVs used in the scenario discussed would be low cost, estimated between $300,000 and $500,000. The low cost can be attributed to the fact that each system in the UUV group is less sophisticated than some of the proposed multi-mission UUVs that are in development. This cost is further reduced by limiting the group to six UUVs, only two of which have ISR gathering masts. Though this cost would not be considered expendable, it is much cheaper than many of the current combat systems on board a submarine.

There are a few possible variations to the scenario, and each would maintain a similar level of maintenance and cost. First, instead of using torpedo tubes, the D5 missile tubes on board SSGN and later Virginia-class submarines could be modified to support the launch and recovery of UUVs. Second, if the ability to recover a UUV is not possible (via a torpedo tube or D5 missile tube) then the UUVs could be either abandoned and self-destructed or retrieved by a surface asset (such as LCS or a DDG). Lastly, to increase the amount of missions performed by the groups, the UUVs could be outfitted with payloads that drop leave-behind sensors and communication nodes, as opposed to staying on station locally.

This scenario is only one of many possible missions, payloads, and CONOPS that can be supported by the 21-inch UUV. The important fact in moving forward is for the Navy to focus on specific missions prior to the systems engineering of an official program.

C. GROUP OF LARGE DIAMETER UUVS

1. Operational Situation

An operational commander has given a forward deployed LCS the order to dispatch a series of Large Diameter UUVs (LDUUVs) to perform a “Hold at Risk” ASW mission near an enemy submarine base. Understanding the risk of detection, the LCS deploys two 48-inch LDUUVs similar in size to Sea Maverick UUV (see Chapter III). The UUVs are programmed to drive into the predetermined “Hold at Risk Zone”

maintaining a persistent, forward barrier, while monitoring the operating area. Upon confirming the identity of an enemy contact, the LDUUV must establish contact with a mission commander in order to obtain mission tasking. However, stealth requirements make it unfeasible for the LDUUV to communicate with the LCS, requiring the operational commander to deploy a Los Angeles-class submarine into the AOI.

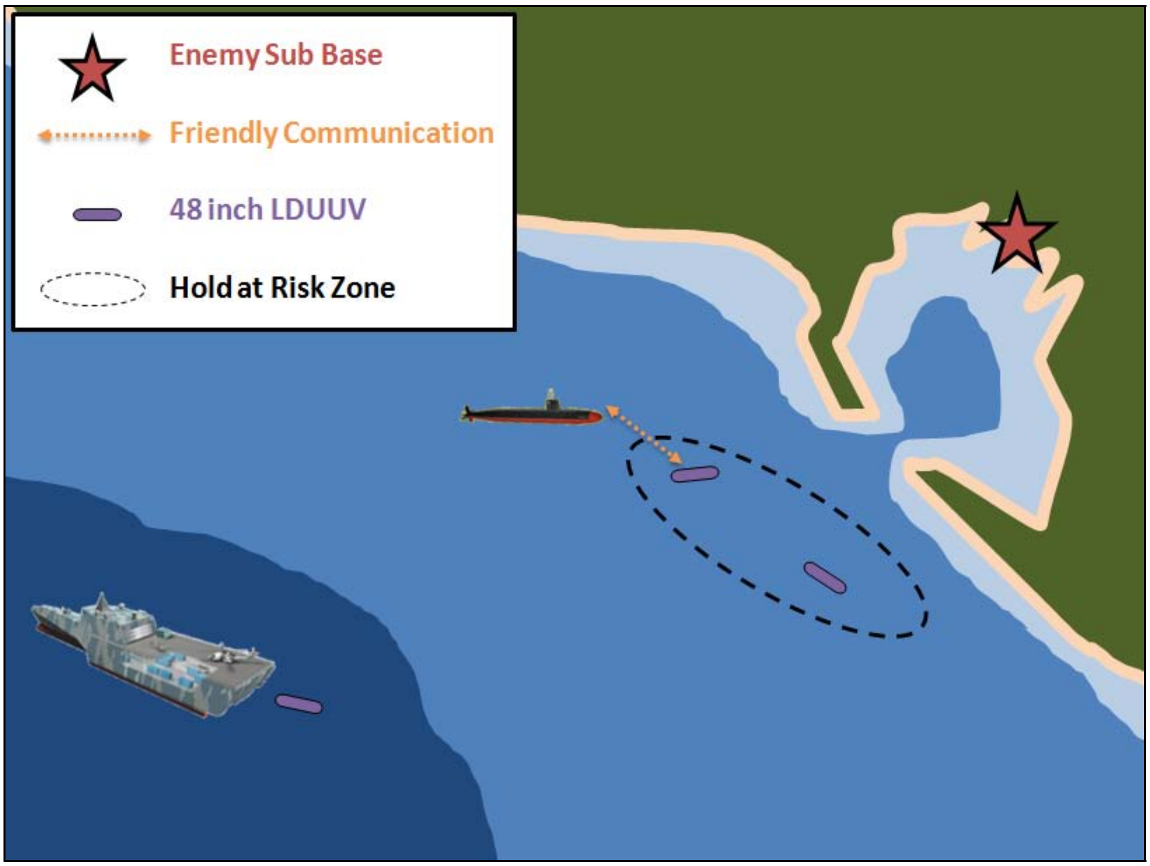

Figure 34. High level graphical depiction of operational situation for a group of LDUUVs

The large size of the LCS mission bay area will allow the ship to easily carry six 48-inch LDUUVs when configured for a Hold as Risk ASW scenario. The number of LDUUVs will allow for the systems to be broken into four different phases:

- **In transit.** The distance of the LCS from the AOI will vary depending on the operational situation, but it will most likely require the LDUUV to

perform a long-range transit into the operating area. The duration of the transit could require one system to always be in this phase. This phase includes both launch and recovery.

- **On station.** The size of the port and demands of the mission will determine the number of systems on station. Though the intent of the entire program would be to have LDUUVs on station, the other three phases will have an impact on the number of on station LDUUVs. The amount of time on station would vary, but a realistic goal of the program should be to allow the LDUUV to remain in the AOI for a more than one day (2-5 days is feasible), anchoring as necessary to conserve resources.

- **Off-line.** Upon recovery, the system will be placed off-line for maintenance, charging, and mission reconfiguration (if necessary). The amount of time in this phase will depend on the vessel status, mission, and type of batteries used.

- **Standby.** After the necessary maintenance and off-line phase, the systems will remain on standby until the mission requires their use. Vehicles in this phase will remain transit ready for quick deployment.

While in the “in transit” phase, the LDUUV will send and receive low bandwidth, mission specific data with the Los Angeles-class submarine operating outside of the “Hold at Risk Zone”. This communication link will allow the commanding officer to determine which targets will be ignored, trailed, or handed off to other assets in the AOI. The long-term situation could utilize a strike/attack option (lethal and non-lethal), but in the short-term, the LDUUVs will only be utilized in a tracking or information gathering mission set.

2. Payloads

There are fewer restrictions on the type of energy source used in the LDUUVs because they will not be deployed from a submarine. The absence of this restraint will allow the LDUUVs to be designed with state-of-the-art lithium battery technology and, as

a result, the LCS deployed vessels will have more endurance, faster speeds, and increased capability in comparison to the torpedo tube launched UUVs. In an effort to increase the number of missions performed by the LDUUVs, the batteries used will most likely be rechargeable. With this in mind, it is important to note that the UUVs could use primary batteries that are swapped out after each mission, though a thorough CBA may determine that this is not the best decision, unless a mission specifically requires the use of primary batteries.

The LDUUVs will be more expensive than the submarine-launched systems. The added cost will be in some of the advanced payloads that will be placed on the larger systems. The payloads will include advanced forward and side scan sonar technologies, advanced identification and filtering software, and multiple different communication packages. A full trade study must be performed to determine the exact systems the LDUUVs will use, but the Navy should recognize that this CONOPS, unlike the previous CONOPS, should prioritize advanced technologies and LCC over acquisition cost savings.

3. Maintenance

It is theoretically possible for a modified SSGN to launch and recover a 48-inch LDUUV, but the advent of the LCS provides several advantages that the submarine cannot. The main benefit of using a support ship is the size of the mission bay (over 15,000 square feet in the LCS-2), allowing for a large space to perform maintenance and store logistic support elements on board.

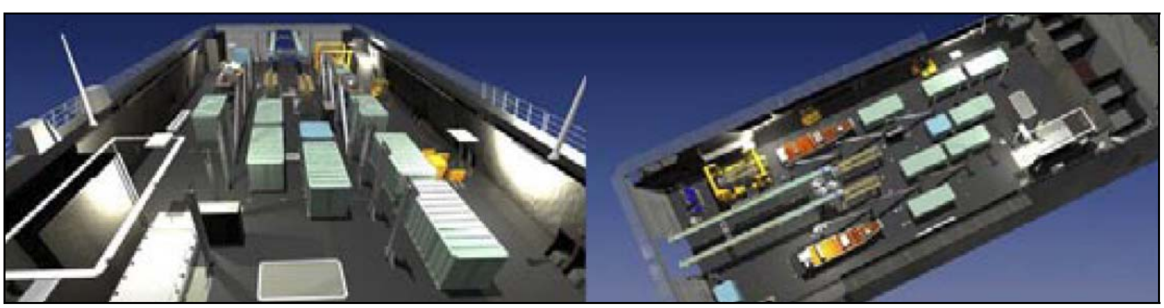

Figure 35. Artist depiction of flexible mission bay in LCS-2 (From: Austal, 2007)

The LCS would perform both organizational and intermediate level maintenance, following a similar model to the HUGIN 1000 as summarized in Table 16. To support long-term operations and flexible mission planning, the LCS mission bay will store several spare parts and multiple mission payloads (sensors, communication equipment, etc.).

Unlike the submarine-launched model, A_o is an important aspect of the LDUUV program. The maintenance performed on board the vessel must be done in a timely manner, increasing the amount of time the vessel can be performing the necessary mission. It is unrealistic and not cost beneficial to have an extremely large A_o. Similar to the LMRS program, a desired A_o should be set between 0.88 – 0.92.

The use of rechargeable batteries will play the most significant role in increasing the MDT and decreasing the operational availability. Focusing on the use of secondary batteries, further research should be conducted to determine if it is possible to use batteries that are replaceable, allowing them to charge while the UUV is conducting mission operations. The use of these would be solely dependent on the tradeoff between charging and battery replacement time. Initial discussions with experts show that battery swapping may be more expensive and time consuming than expected, but still offers some room for increased availability.

The system reliability must be at the forefront of system requirements. Reliability is driven by the number of failures, and a program that is completing sensitive missions in unfriendly waters cannot run the risk of having high failure modes. The two design factors than can increase reliability are robust component design and redundancy. Both are not cost effective, but are necessary in maintaining the standards the Navy will need for a successful program. For some cost savings, a full analysis, similar to "UAV Lesson 7," should be performed to ensure the systems are not over designed. If the data is similar to UAVs, three levels of redundancy will most likely prove to be the most beneficial.

4. Manning

The use of a LCS and SSN will require both vessels to have manning to support the ASW mission. Similar to the other CONOP, the manning estimates do not take into account any intelligence personnel that may be required to complete the specific missions.

The demand registered by the LCS will require as many as ten Navy detachment and contractors to perform maintenance and launch and recovery supervision. The nature of the missions will require personnel to be available around-the-clock in support of the efforts. This number will be higher if ship's force is unable to assist in the launch and recovery of the LDUUVs.

Though the submarine will not be performing launch and recovery or maintenance, the onboard manning requirement would still be comparable to the torpedo tube launched CONOPS. The long endurance capability of each LDUUV coupled with the cycling of systems on station could lead to an around the clock watch station for greater than 30 days. This leads to a minimum of one supervisor and three other detachment-based personnel to operate the communications equipment and direct mission-tasking between the UUV and submarine. Unlike the previous CONOPS, with minimal training the mission could be completed by ship's force and require only one detachment based supervisor during each deployment. Lastly, a contractor or two may be necessary (but not required) to support maintenance on the communication system or mission console.

5. Recommendations

The LDUUV program provides different opportunities than the submarine-launched 21-inch UUV, but with it comes various challenges. Naval leadership would prefer to have up to 30 days of persistent, sustained UUV operations, but this goal is not realistic in the short term. Instead, the use of a group of vehicles that cycle between maintenance (off-line and standby) and operation (in transit and on station) phases will allow for the mission sets of a long endurance UUV without the technical challenges.

The only realistic, short-term way to service the LDUUVs is through a support ship operation. Due to the nature of the forward deployed missions, the support ship cannot be a research vessel, but must be a warship. With that, LCS is not the only platform possible but it does provide some important benefits in comparison to the alternatives, including the modular mission support and large mission bay. It is important that Navy not only start developing a submarine UUV program that uses the LCS as a valuable resource for operational supportability but also to focus on it at the beginning stages of program development.

ISR is the leading mission candidate for the first submarine program of record. Though this CONOPS focused on an ASW mission, the principles can be applied to many of the missions outlined in the 2004 Navy UUV Master Plan (Department of the Navy, 2004). Unlike the smaller UUVs which are low cost, short of physical space on board, and lack logistic supportability, the LDUUV can be designed to be more mission reconfigurable, with interchangeable payloads and sensors. Even with this ability, the Navy should still keep their short-term focus on a single (or closely related) mission(s) requiring the fewest number of design configurations and logistical support pieces.

D. CHAPTER SUMMARY

The purpose of this chapter was to introduce two specific CONOPS that the Navy can consider for two successful submarine UUV programs. Time, resource, scope, and classification constraints of this thesis have limited the amount of details in these CONOPS, but the big picture ideas discussed should be brought to the forefront of UUV decision making, starting with the mission definition in the systems engineering process. With that, the important take away from this chapter is the specifically defined missions of the UUVs, increasing the odds of a successful DoD program.

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VII. CONCLUSIONS AND RECOMMENDATIONS

A. INTRODUCTION

This thesis used government and industry resources to focus on the systems engineering fundamentals that are necessary to have a successful submarine UUV program of record. To do this, systems and missions needed to be researched and discussed to ensure that both the author and reader have similar understandings to the scope of the research. Additionally, these sections have attempted to break down the "stove-piped" research currently taking place in the areas of commercial and militarized UUVs. A majority of the discussion outside of the systems engineering discussion and sample CONOPS (Chapters V and VI) is well understood by the industry's and Navy's top UUV experts, but it is information that is not known, understood, or otherwise available to some of the decision makers that are directly responsible for the success (or failure) of current and future programs.

The systems engineering discussion and CONOPS portion of this thesis combine the ideas that are presented in Chapters II-IV to propose actions and procedures that are lacking in the current development of a submarine UUV program. This section will summarize those conclusions and recommendations, and furthermore, will offer the Navy decision makers some ideas in regards to what needs to be done to create a near-term, formal, and successful program of record.

This section summarizes the answers to the research questions posed in the introduction. The five questions answered by this thesis are:

1. Which UUV missions are most likely to occur in the near future? Are these missions feasible for the Navy?
2. Which of the UUV missions are most applicable to support the submarine force? Will these missions require deployment/retrieval from a submarine platform?

3. Have unmanned ground vehicles (UGVs) and unmanned aerial vehicles (UAVs) provided any lessons learned during their employment in military operations?

4. Will UUVs have a detachment to support their use, or will they utilize ship’s force? Will the operators be contractors or military? If military, which ratings will be used to operate these systems? Will additional ratings be necessary to accommodate the mission sets? What training is necessary for the operators?

5. What changes in the current infrastructure for maintenance and system support are necessary to complete the missions of both the UUVs and submarines? Can the maintenance be done on board (operator level), or will other vessels and facilities be required? Does the use of UUVs change the original schedule of the host submarine?

B. CONCLUSIONS AND RECOMMENDATIONS

The government is devoting much effort in the formal training and proper utilization of Systems Engineers. As a result, many programs are seeing an increase in their productivity during the early stages of lifecycle development. Unfortunately, many programs are being researched and tested using informal processes through government organizations like ONR and DARPA and are ultimately cancelled due to funding concerns. Though there is a place for research and development of technologies, the current procedures are sidelining UUV programs that have performed up to, and in some cases beyond, operator’s expectations. Many programs in development are outside the needs of preliminary development and must be pursued in the form of a formal program. To ensure a successful DoD program, the systems will need to be developed using a formal systems engineering process. Adhering to these processes will ensure that a successful program will retain funding.

To do this, the Navy must start with a clearly defined mission and then follow four basic steps to develop the ideas into systems. These steps, in order, are: develop requirements, determine tasks, create functions, and design components. This will

require the government to produce ideas independent of the end product in mind. This means that the decision makers will have to change the desire of a "30 day submarine launched UUV" to that of "covert UUV systems capable of sustaining a 30 day ISR mission." In most cases, these two sentences may appear to be the same from the point of view of the decision makers, but will yield completely different desires and outcomes at the developmental levels. The first requires technologies that are unproven, expensive, and long term; the second can be completed in the near future with systems currently under development.

The intent of the thesis was to analyze the impact of a submarine UUV program on the manning and maintenance of the submarine force. Outside of the systems engineering and development process concerns discussed previously, this thesis comes to three conclusions: focus the missions, learn lessons from UGVs and UAVs, and consider manning and maintainability.

1. Focus the Missions

The 2004 UUV Master Plan outlines nine distinct Navy missions that can be accomplished by UUVs (Department of the Navy, 2004). Though these missions were listed in "priority" order, they do not take into account near term feasibility or applicability for use by the submarine force. As a result, this thesis focused on only two of the nine missions for those that are applicable for a submarine UUV program of the near future: ISR and ASW. Additionally, a third mission, communications (a derivation of the Navy sub-pillar of CN3) must be accomplished to ensure success of any submarine UUV program. These two (or three) missions are most easily accomplished with the current technologies used by industry and government resources.

The challenges (other than budgetary considerations) that face current ISR and ASW missions are longevity and launch/recovery. The research suggested ways of creating programs that will gain successful mission results in the near term while still adhering to the technical constraints faced by UUV developers.

The Navy would prefer a long endurance vehicle (30 days or more), which is not feasible in the short-term, but this can be countered by the use of multiple UUVs rotating

in and out of the AOI, completing the same mission as a single long endurance vessel. This idea comes with risks, but it is a feasible option to research and evaluate. Additionally, there are proven launch/recovery assets possessed by foreign governments and past Navy programs. In the short term, however, the most viable option, without significant changes to current submarines, is either a launch without recovery option (where the recovery could be done with the use of a support ship) or a support ship launch and recovery.

2. Learn Lessons From UGVs and UAVs

UGVs and UAVs provide several similarities to UUVs and were the basis for eleven lessons learned pertaining to the development of UUV systems. The eleven lessons were diverse in their relation to UUVs, but all provided ideas that should be considered during the front-end system development process that directly relate to the manning and maintainability of a program of record. These lessons (along with any others shared amongst the program offices) should all be considered prior to spending more money on testing, developing, and fielding new unmanned systems.

3. Consider Manning and Maintainability

The original intent of the research was to understand the manning and maintenance models and concerns that UUVs would have on the submarine force. Past systems have neglected the impact of logistics on the deployment of new systems, and it is important that the developers of a submarine UUV program do not forget this. The limited size, space, and crew aboard a SSN will require these thoughts to be fully considered before the program enters the advanced development stages.

a. Manning Models and Ratings

Unmanned systems have not had simple transitions into the military. During the transitions, personnel are trained to be both the equipment operators and maintenance experts. This practice has been no different in the UUV community. This gives the Navy two options: (a) train a large number of submarine qualified enlisted, Warrant Officer, and LDO ranks to operate and maintain the equipment, thus manning

each boat with qualified personnel, or (b) use a detachment of trained cadre experts to act as temporary resources aboard the vessels utilizing the complex UUV equipment. In the long term, when each submarine is equipped with multiple UUV systems performing a variety of missions, the Navy will need to have some number of trained sailors serving as ship's force on all deployed submarines. In the short term, it is more realistic to continue the use of UUV detachments to support the programs as they are deployed on a small number of submarines.

Depending on the mission and operational model used, the detachment size will vary. According to various experts, the minimum manning for a submarine launched UUV program would be directly correlated to the number of UUV systems operated and maintained on board the submarine. In each case, the manning model would utilize one supervisor, plus:

- 2 personnel for 1 UUV
- 3 personnel for 2-3 UUVs
- 4 personnel for 4-6 UUVs

This model, as utilized in Chapter VI, does take into account contractors for maintenance, but ignores the addition of intelligence personnel necessary to support the missions. Experts estimate that the model for the LDUUV example would require 4-5 personnel on board the submarine (no contractors necessary) and a complement of 10 on board the support vessel (including contractors). This increase in manning would support the longer, more maintenance-intense missions of the larger UUVs.

The operator ratings vary in the UUV community, but are currently limited to submarine qualified ET, FT, MM, and ST. The Navy has considered the idea of creating unmanned systems ratings for both the UAV and UUV communities, but this step is considered unnecessary and is discouraged by those in the submarine related UUV community. Currently, the diverse experience and required submarine warfare qualification of a current UUV operator (under NEC 9550) is valued more than a specific rating. Additionally, there is not short-term need for very junior (E-4 and below) and senior (E-9) personnel to demand a rating change.

b. Maintenance and Logistic Support

DoD systems are serviced at three different levels of maintenance: organizational, intermediate, and depot. Submarines do not provide the space needed to provide extensive maintenance of UUVs, making it difficult to perform the organizational level routines common to unmanned systems. Two maintenance models can be used to support the organizational level maintenance for a submarine UUV program:

- **Limit Duty Cycles.** The lack of maintenance performed by the operators aboard submarines will limit the duty cycles that an individual system can perform during each submarine deployment. This option increases the intermediate level maintenance burden, but provides the ability to perform a submarine-only launch and recovery of UUVs.

- **Utilize a Support Ship.** Support ships, such as the LCS, provide large areas to perform both organizational and intermediate level maintenance. These options will increase the number of times a UUV can be utilized during a deployment, but reduces the stealth nature of the operations and may limit the number of missions that the support ship can assist and perform. This method should be the preferred choice for larger UUVs.

The systems developed should not be "platform centric," allowing them to be used with multiple launch and recovery systems (with little to no system modification). Even with a modular approach, the systems must consider supportability during their design phases. The power source, payload, and communications suites should not be designed without regard of the type of organizational (and intermediate) levels of maintenance to be performed.

C. AREAS OF FURTHER RESEARCH

The intent of this thesis has been to focus on the abstract, high-level concepts that will affect the manning and maintainability aspects of the systems engineering process.

As a result, the scope of this thesis has led to several areas of further research for future studies. The future work to expand this thesis into real world applications should be done in the areas of trade studies, technologies, lessons learned, and requirements.

1. Perform Trade Studies

In an effort to field UUVs in the near future, several trade studies will need to be performed using current levels of technologies. Many of the current projects being developed for submarine use attempt to combine an abundance of "top of the line" features that are proving to be infeasible for successful development in the short term. Trade studies that should be performed that may directly lead to the success of a short-term program and/or reduce LCC are to optimize MTBM, perform manning studies, maximize mission time, and enhance communications.

a. Optimize MTBM

An increase in the MTBM will reduce the maintenance and logistics cost but will increase the upfront acquisition costs. A trade study will need to be performed on various maintenance metrics (mainly MTBM, but should also apply to MDT, reliability, and number of redundant components) and compare the cost of implementing the proposed changes and the effect that it will have on LCC. Another area that could be involved in this study would be the number of duty cycles performed by each system.

b. Perform Manning Studies

A majority of the manning conclusions developed in this thesis came from the opinions of experts who are currently working on the development of UUVs and submarine UUVs. Though their opinions are highly valuable and are credible for the basis of the discussion in this thesis, formal studies will need to be performed to understand the trade-off between personnel and LCC. The two major questions that will need to be answered are 1) how many systems can one operator manage simultaneously and 2) how many personnel are required to perform the organizational and/or

intermediate levels of maintenance required at sea? The answers to these questions will then need to take into account the specific ratings of the operators as well as whether they must (or can) be detachment based personnel.

c. Maximize Mission Time, Not Endurance

A reoccurring theme in this thesis and the unmanned vehicle world has to do with endurance. This study has suggested that the desire for long endurance missions may be an unsubstantiated one and multiple platforms rotating in and out of the AOI may give the same result as one platform staying on station for a long period of time. This theory will need further analysis to determine the impact several systems have on the overall cohesiveness of the mission. Ultimately, the goal of the programs should be to maximize the mission time. Ideally this would be done with a high endurance vehicle, but there are other options (especially in the short term) to consider without the costly technical challenges of maximizing endurance.

d. Enhance Communications and Node Concepts

Undersea communications (for this thesis mainly ACOMMS is presented) are limiting in range and bandwidth. The stated CONOPS would need to be analyzed to determine if ACOMMS (or other) undersea communications are able to send the desired mission data between UUV nodes, or if these platforms will need to surface and use air as the medium for communication. In this case, the quality of the signal would need to be balanced with the risk of using surfaced vessels and over the air signals. Additionally, the feasibility of leave behind nodes will need to be further analyzed.

2. Develop and Advance Technologies

The area that is currently getting the most focus is the development of new technologies and advancement of current technologies. The trade studies should be used to determine the best solution using existing technologies, but this does not mean to say we should ignore the many areas of growing technology that currently support UUV missions. In both cases of current and future technologies, research should be focused on the maturation and militarization of the technologies over the theoretical and commercial

nature of the technologies as done by the industry today. It is important that the stakeholders and developers understand the difference (if there is one) between the commercial and military standards of the technologies that are being developed.

The three technical areas that need the most research to ensure the success of a submarine UUV program are: power (battery, fuel cell, or other), communications (above and below the surface), and launch/recovery. These areas have been the focus extensive research efforts, but not specifically in the realm of militarization and submarine-based programs.

3. Summarize Lessons Learned

UUV programs can find valuable lessons learned from both UUV programs of the past and other unmanned programs. Both of these can be derived and analyzed in different ways and can provide valuable insight into increasing the chance of success of a UUV submarine program of the future. The data shared amongst the programs (UUV to UUV and UGV/UAV to UUV) should consist of both operational and technical data.

a. Lessons From Other UUV Programs

As discussed earlier, the ADO has been implemented as a means of sharing data amongst the unmanned systems programs of the Navy. Though this thesis used past and current programs/projects to develop ideas for future CONOPS, it did not specifically list and describe lessons that can be learned from the successful and, perhaps more importantly, the unsuccessful programs. Though the program offices (in this case the ADO) know some of the key lessons they have learned, a formal list would be extremely beneficial to all programs of the future.

b. Lessons From UGVs and UAVs

Chapter IV focused on the lessons that can be taken from UGVs and UAVs and implement in the UUV community. This section has the ability to be expanded into an entire study/thesis, focusing on the implementation and direct

correlation of these lessons. For example, Table 8 and Table 9 discuss the various UGV vehicle classes and how they relate to human operators and similar tables could be researched and created for UUV platforms.

Additional studies could focus on the relationship between water-space and air-space management data, the use of a single operator to control multiple platforms, maintenance routines, and non-lethal (and eventually lethal) engagement sequences.

4. Concentrate on Requirements

The case studies analyzed in this thesis discussed the importance of requirements, but did not use actual USN requirements during the development of the CONOPS. Most of the programs of the past and present have had formal requirements documents. A future study should utilize these documents and correspondence with the program offices, DARPA, and DEVRON 5 UUV Detachment personnel to determine a basic set of necessary requirements for a future UUV program. These requirements should be set independent of the vehicles, platforms, and technologies currently being explored as UUV "projects."

D. CHAPTER SUMMARY

This chapter provided a summary for the thesis. It expanded upon concepts that were introduced and discussed during the body of the thesis and brought them together for a succinct summary of the author's opinions on how the Navy should implement a submarine UUV program in the near future. The Navy must develop formal CONOPS for the missions and systems that it wants to produce and allow industry to begin development for a formal future UUV program. Furthermore, analysis suggests that the Navy should continue to support the use of a submarine detachment for operation and maintainability of future vehicle programs.

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